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Ocean Eddies

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Front cover: Schematic representation of types and distribution of variability in the western North Atlantic and locations of major experiments completed. Figure 7, page 12, presents a more detailed map of experimental sites including proposed research. (Drawing by Nancy Barnes, based on map by William Simmons)

Back cover: The "effective" bottom topography of a 2000-kilometer-square computer ocean model. This consists of the actual rises and valleys of the sea floor, plus a gentle upslope to the north. It is now evident that ocean eddies, even near the surface, are critically sensitive to these hills. See page 36. (From P. Rhines, "The dynamics of unsteady currents," in The Sea, *vol. 6,* Marine Modeling, *edited by E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, to be published in 1976 by John Wiley & Sons, New York.)*

Eddies and Ocean Circulation

by Allan R. Robinson

The motion of the water in the oceans occurs in a great variety of forms; from surface waves and ripples that slowly undulate or heave and break with foam and spray, to systems of deep subsurface currents that interconnect the many seas and oceans and course from pole to pole. To describe the motion of the water many scales of variability must be invoked, ranging in size from millimeters to the circumference of the earth itself and in duration from seconds to centuries and longer. Corresponding to the description of the motion associated with different time and space scales are different physical phenomena, for example, tides and waves and currents. These occur not only because of the many forces acting upon the waters of the ocean, but also because of the interplay among the various phenomena or different scales of motion themselves.

By the general circulation of the ocean is meant the pattern of flow throughout the world ocean that occurs on the global scale on the average over many years. The concept is simple, and many features are unambiguous, but a little thought indicates that a precise definition involves some subtleties. For example, the spatial averaging must describe the permanent currents like the Gulf Stream, which, although thousands of kilometers in extent, is less than a hundred kilometers in width. The time averaging must contend with the very slow changes that are occurring in the ocean, such as the gradual rise in sea level over thousands of years due to the melting of the polar ice caps.

Because of the great difficulty in obtaining adequate and representative observations, our present description of the circulation is indefinite and in many aspects incomplete. However, oceanography, like many of its sister earth sciences, is in a state of rapid evolution. Technical and instrumental advances are making it possible for oceanographers to obtain for the first time the kind of data necessary for a realistic attack on the physical problems of the general circulation. Moreover, this is occurring at a time when advances in the understanding of similar fluid dynamical systems, such as the atmosphere, provide a basis of physical ideas and theoretical techniques that can usefully be adapted and developed for the ocean problem. It is an exciting prospect for physical scientists to be at even the initial stages of understanding a major component of their planet. In addition to the motivation of natural curiosity, there are practical reasons for the study of the ocean circulation. Since the circulation influences climate, the global distribution of chemicals, and the biological productivity of the sea, increasing our knowledge of circulation could benefit society by contributing to the rational management of the planetary environment and resources.

The movement of the water affects and is affected by the distributions throughout the oceans of the pressure and density of the water. Differences in density are directly related to the temperature (heat content) and salinity (salt content) of the water. The scientific problem of general circulation is to account for and predict the distributions of water velocity, pressure, and density in terms of the external forces that drive the ocean—primarily the action of wind forces and the heating and cooling of the water at the sea surface. Obversely, and most importantly, an understanding of the circulation implies a knowledge of the input of heat momentum and energy into the ocean, of the mechanisms and motions that carry these quantities around and redistribute them, and their ultimate fate. Where does the energy of the

circulation come from, where does it go, and how does it get there?

That the ocean circulation itself is in part responsible for the global distribution at the sea surface of heat and energy exchange between the ocean and the atmosphere is well known, although the exchange process itself is not at all well understood. The fundamental problem is the coupled general circulation of the atmosphere-ocean system, the basic energy source for motions of both air and water being the incoming radiation from the sun. Thus, atmospheric winds, temperatures, and rainfall, the weather and the climate of the earth, are affected by the oceans, even over land. The dynamics of climatic variations—that is, the evolution of the coupled air-sea systems that occur over years, decades, and centuries—are probably most importantly influenced by the dynamics of the ocean circulation because of the relatively high heat capacity of the oceans and because of the slow movement of the deep water.

A knowledge of the global distribution of many chemicals and the changes over time of distribution patterns is of importance to man. Dissolved chemicals, including carbon dioxide and other waste products of an industrialized society, are carried about by the circulation, which also influences and helps to control the rate and distribution of the exchange of the chemicals with the atmosphere across the air-sea interface. Thus the distribution of chemicals throughout the atmosphere, including the stratosphere, can be interdependent with that of the deep ocean.

The distribution and population of living resources in the sea is also coupled to the circulation. At the heart of the ecological system lie tiny organisms that are moved about totally or partially by the motion of the water, which also transports vital chemical nutrients. Photosynthesis, which is essential in the biological cycle, can only take place within about 100 meters of the surface—the depth beyond which sunlight does not generally penetrate. Biologically rich and fertile regions of the sea are those where upwelling occurs, that is, where the circulation has an upward component of motion that continually brings nutrient-rich water from the deep ocean into the near-surface layer. Unusual or unexpected changes in the circulation that suppress upwelling can have dramatic effects on the productivity of traditionally fertile fishing grounds, such as the almost total annihilation of the anchovy crop off the coast of Peru during 1971-72.

Physical oceanography is evolving from a descriptive, naturalistic subject into a modern geophysical science solidly based in the fundamental disciplines of applied mathematics and physics. Deep-sea research expeditions are becoming scientific experiments designed to answer specific physical questions. Interplay between theoretician and experimentalist is developing. Our understanding of the circulation lies not only in the body of interpreted observational data, but also in the conceptual models constructed by theoreticians (see page 28). These models represent the particular form that the fundamental physical laws are believed to take when applied to the governing of the ocean circulation. Their mathematical expressions, translated into languages used by modern high-speed computing machines, are called numerical models. As our knowledge of the circulation improves, so does the physical basis of our modeling. An ultimate goal is to construct a model of the ocean circulation that is a good enough physical analogue of the real ocean so that credible applications can be made to the study of climate, geochemistry, and biology. Such studies involve the coupling of numerical models of the general ocean circulation to atmospheric, chemical, and biological numerical models.

The general ocean circulation has been defined as the long-time average, global-scale flow that occurs in an oceanic environment rich in flow phenomena on many scales. During the past two or three decades, new observations have begun to identify a phenomenon that appears to be intimately linked physically to the general circulation, and even to dominate the circulation energetically in many regions. This phenomenon is comprised of slow, medium-sized fluctuations in the circulation itself. These fluctuations, technically named the low-frequency, mesoscale variability, are commonly called the eddying of the flow. We now know that the variability can take several forms, such as meandering of the Gulf Stream, large ring vortices that are snapped off from the currents during intense meandering events (see pages 65 and 69), and the mid-ocean eddies. The latter form of the variability, first suggested by the results of the *Aries* expedition in 1959-60, can be a hundred times more energetic than the background average circulation. Mid-ocean eddies extend from the sea surface to the bottom, have a radius typically of 100 or 200 kilometers, and take a few months to pass by a given location in the ocean. Their discovery has significantly changed our ideas and our models of the general circulation, influenced the direction of contemporary research, and led to major and intensive research programs dedicated to their exploration. In retrospect, however, their existence is not surprising; they are the deep-ocean

counterpart of storms and weather systems in the atmosphere. Although the major high- and low-pressure systems in the air encircling the globe at mid-latitudes are thousands of kilometers in extent and take only a few days to pass, their natural time and space scales are dynamically similar to those of ocean eddies (see page 77). Because properties of seawater, such as density, are different from those of air, dynamically similar events occur in the ocean in a more compact, slower form than in the atmosphere. This is most unfortunate for the oceanographer faced with the logistics of their investigation—the ocean appears to be filled with many slowly evolving storms. The prospect of even a single global oceanic "weather map" comparable to those obtained daily on a routine basis for the atmosphere is hopelessly remote. Even the initial exploration of phenomena that has documented the existence of eddies and described their characteristics in two locations in the North Atlantic required many ships and instruments, and the cooperative efforts of many oceanographers and several institutions and nations.

Physically realistic modeling and a breakthrough in understanding of the atmospheric general circulation came in the mid-twentieth century with the explicit inclusion of the cyclones and anticyclones in the models and a recognition of their fundamental role in the long-time average global circulation. The winds associated with the atmospheric eddies vanish when the time averaging of the air flow that defines the atmospheric general circulation is performed. But the influence of the atmospheric eddies does not disappear. Their essential role in the atmospheric general circulation is to draw energy from the mean density distribution in the atmosphere, transport heat from the equator to the poles, and transfer energy into the mean winds that blow around the earth at mid-latitudes.

We do not yet know what is the essential role in the oceanic general circulation of the oceanic eddies. The related atmospheric phenomenon provides insight and helps to guide our research. Although the oceanic eddies are thought to be dynamically analogous to the atmospheric, it is unlikely that their physical role in the oceanic general circulation is identical to that of the atmospheric systems in the atmospheric general circulation. Where does the ocean eddy energy come from, where does it go, and, on the average, what is the role of eddies in the general ocean circulation? Given the strength and ubiquitous nature of eddies, they probably contribute substantially to the mean transfer of properties of vital interest to climatologists, geochemists, and biologists. Before the questions concerning the role of the eddies in the circulation and in the transfer of properties can be adequately addressed, considerable research effort must continue to define the characteristics and distribution of the phenomenon.

The classical picture of the general ocean circulation was pieced together from data, mostly of an indirect nature, taken over many years. Direct measurements of ocean currents have become possible over the vast depths of the open ocean only recently. Since the flow is slow, attempts to measure it directly by instruments attached to drifting ships were frustrated by errors of navigation. Early evidence consisted only of surface currents plus the distribution in depth of observable properties, such as temperature and salinity. Nonetheless, from this data there emerged a description of the circulation containing certain striking overall features. Examination of the worldwide pattern of surface currents (Figure 1) reveals certain regularities. Except for Antarctica, where the water flows freely around the globe, the water is contained in several interconnected basins bounded by continental land masses. The flow is roughly symmetrical about the equator, North and South, and each major ocean basin (that is, North Atlantic, South Atlantic, North Pacific, South Pacific, and Indian oceans) has a similar structure of circulation. The most important feature in each basin is a large circulatory pattern or vortex called the main subtropical gyre. In the map of Figure 1, for example, it appears to lie between about 10°N and 50°N latitude in the North Atlantic. To the south, there is an equatorial current system and to the north a smaller vortex with circulation in the opposite direction called the subpolar gyre. The circulation in the main subtropical gyre has a high degree of east-west asymmetry. A very strong northward flow occurs in a very narrow intense current—the Gulf Stream near the coast of the United States—while the much slower southward flow is distributed across the gyre. The North Pacific gyre has a similar strong current off the coast of Japan called the Kuroshio. This description of the flow is not limited to surface waters, as is shown by the classical pattern of the North Atlantic transport, the average overdepth of the horizontal velocity (Figure 2).

The subsurface description of the circulation was obtained from the analysis and synthesis of the data from hydrographic stations. At each station water samples were collected from several depths and analyzed for the *in situ* temperature, salinity, and other properties, such as

percentage content of dissolved chemicals. Information about the circulation is inferred in two ways. The first is called water-mass analysis—an attempt to account for the distribution of all the properties of the water by the mechanism of determining where the water must have come from in order to have those properties. This type of analysis indicates that the water involved in the very deep general circulation comes from two rather limited sinking regions located in the polar regions of the North and South Atlantics.

The second method of inferring subsurface circulation involves so-called geostrophic computations. If the pattern and distribution of pressure is known in the atmosphere or ocean, the wind or current can be computed approximately, but quite accurately. At any level, the horizontal velocity is proportional to the horizontal pressure gradient, or difference in pressure between two points. In other words, given at any level a map of lines of constant pressure, the flow will be along those lines at speeds that are predictable. This type of approximate flow, which is related to the spinning of the earth about its axis, is the basis of the common interpretation of atmospheric weather maps, where the winds circulate clockwise and anticlockwise around the centers of the high- and low-pressure systems.

The pressure distribution in the ocean depends upon the distribution of density with depth and the distribution of the height of the sea surface (because of the presence of currents, the sea surface is not level). Unfortunately, sea level differences as small as several centimeters across as large a distance as a thousand kilometers can produce a significant current (several centimeters per second). But sea level differences as small as this cannot as yet be measured. Thus the oceanographer has been limited to the knowledge of only that part of the current resulting from pressure differences that are due to observable differences of density (that is, temperature and salinity). In practical terms this means that a horizontal temperature difference implies a vertical difference in horizontal flow. Large local horizontal temperature gradients imply strong horizontal currents, and oceanographers commonly use maps and sections of the temperature distribution and "see" the relative currents, as illustrated in Figure 3. A striking feature of the temperature distribution is the fact that much stronger vertical and horizontal temperature gradients exist in the upper few hundred meters of the ocean, the region of the main thermocline, than below the thermocline. The deeper flow is therefore slower and more uniform in depth. It is the main thermocline transport that is shown in Figure 2.

The picture of the general ocean circulation that is emerging has certain gross features that were first accounted for in terms of simple theoretical models in the productive and exciting period from the late 1940s through the early 1960s. These features are the similarity of the flow pattern in the major ocean basins; the existence of the subtropical and subpolar gyres; the east-west asymmetry of the gyres and the existence of the intense western boundary currents like the Gulf Stream; the structure of the main thermocline; and the existence of very limited sinking regions that provide the water masses for the deep circulation of the whole world ocean. The theoretical models took into account the overall pattern of the surface wind stress on the ocean, the general equatorial heating and polar cooling of the ocean surface, and considered the implication, in idealized form, of the geometry of the ocean basins and the consequences of the spinning earth. Figure 4 describes in schematic form the horizontal circulation pattern of an idealized ocean basin, and Figure 5 presents the pattern of transport obtained in a simple theoretical model of typical subtropical and subpolar gyres. The three-dimensional circulation pattern in an idealized basin is shown schematically in Figure 6. The force of the wind blowing on the sea surface produces a clockwise gyre in the main thermocline with a strong Gulf Stream. This is reinforced by the thermally forced circulation, which has as distinctive features a limited concentrated sinking region that acts as a source for a southward-flowing deep countercurrent below the Gulf Stream. In the interior of the deep ocean, below the main thermocline, there is a slow upwelling of water everywhere supported by a slow broad drift to the north at less than 1 centimeter per second (that is, less than 1 kilometer per day). This type of flow pattern was first obtained in simple theoretical models and subsequently reproduced, explored, and developed on the computer via numerical models.

The success of the models in qualitatively describing gross features of the classical data base suggested that the physical mechanisms upon which the models are based are of real significance in the ocean circulation. Quantitative assessment was more difficult, but the theoretically predicted Gulf Stream transport, although low, was in general agreement with the best available observational estimates. The best test of a theory is its ability to predict new facts, and in 1957 the existence of a deep thermal countercurrent under the Gulf Stream was verified

Figure 1. Major features of the surface circulation of the oceans. (After McLellan, 1965)


West Greenland C.
East Greenland Current
Irminger
Labrador C.
N. Atlantic C.
Gulf Stream
Florida C.
N. Equatorial C.
Guiana C.
E. Counter C.
Guinea C.
South Equatorial C.
Brazil Current
Benguela C.
Agulhas C.
Humbolt Current
Falkland C.
N. Equatorial C.
Equatorial Counter C.
South Equatorial C.
Antarctic Circumpolar Current
80°
60°
40°
20°
0
0°

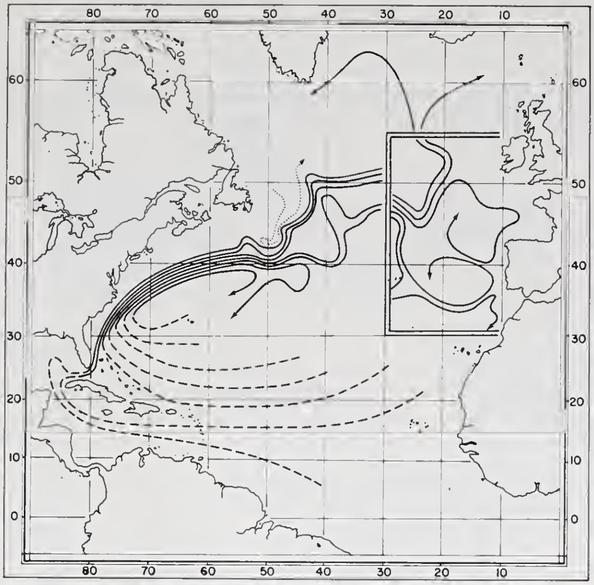
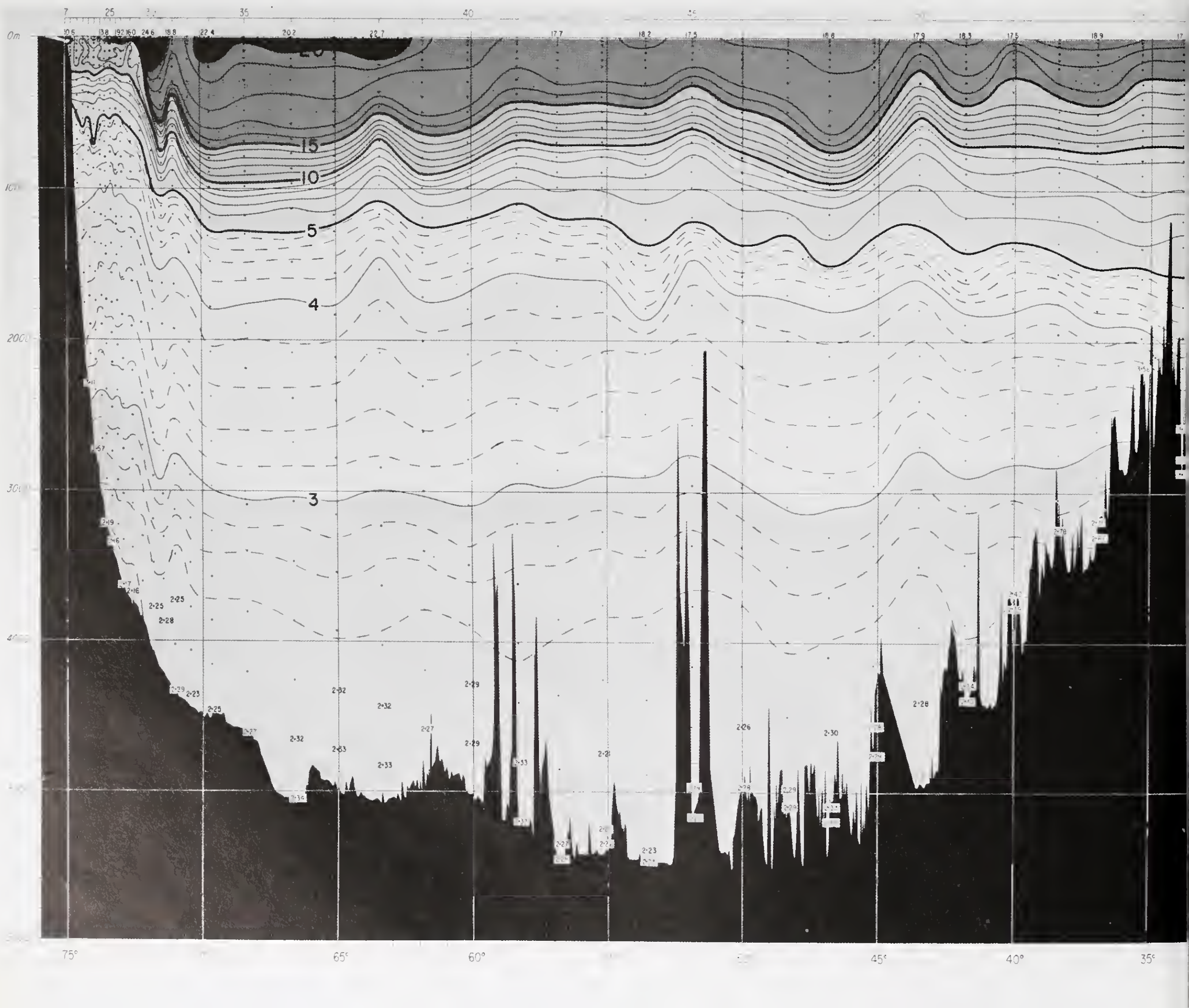
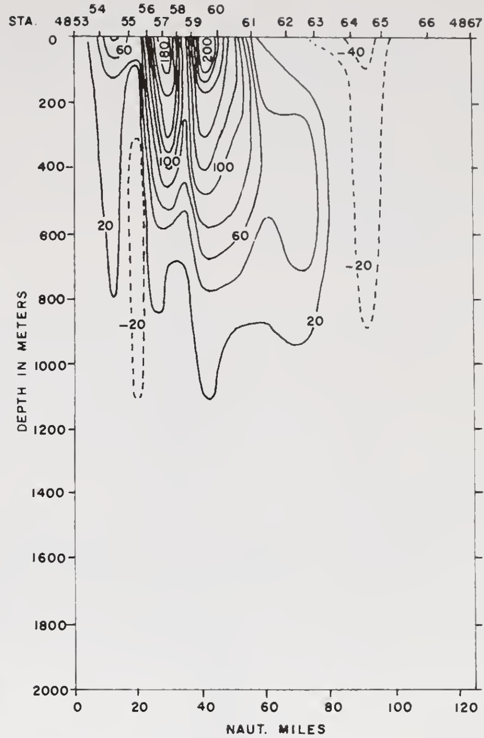


Figure 2. (Left) Streamlines of transport of the Gulf Stream (solid lines) and its source region (dotted lines). The amount of water flowing between any two lines is equal so that where the lines are close together the flow is swift, and where they are far apart it is slow. (After Iselin, 1936)

Figure 3. A vertical cross-section (below) of the North Atlantic at 36°N latitude. Lines of constant temperature (isotherms) are in degrees Centigrade. The near-surface isotherms slope upward to the east across the basin, with fluctuations that are now known to be caused by mid-ocean eddies, although in this cross-section the horizontal spacing of observations does not resolve the structures of the eddies. The very sharp rise to the surface in the west is the Gulf Stream. Note that the vertical scale is 6 kilometers, whereas the horizontal scale is about 6300 kilometers, which results in a distorted bottom topography. (Opposite page, top right) A calculation that shows lines of constant speed (in centimeters per second) in the Gulf Stream from the associated local temperature map (opposite page, bottom right). These kinds of classical data have been obtained from the analysis of seawater collected in Nansen bottles (opposite page, top left), which are lowered on a cable over the side of the ship. (Below: adapted from Fuglister, 1960. Opposite page: right, after Worthington, 1954; top left, Woods Hole Oceanographic Institution.)

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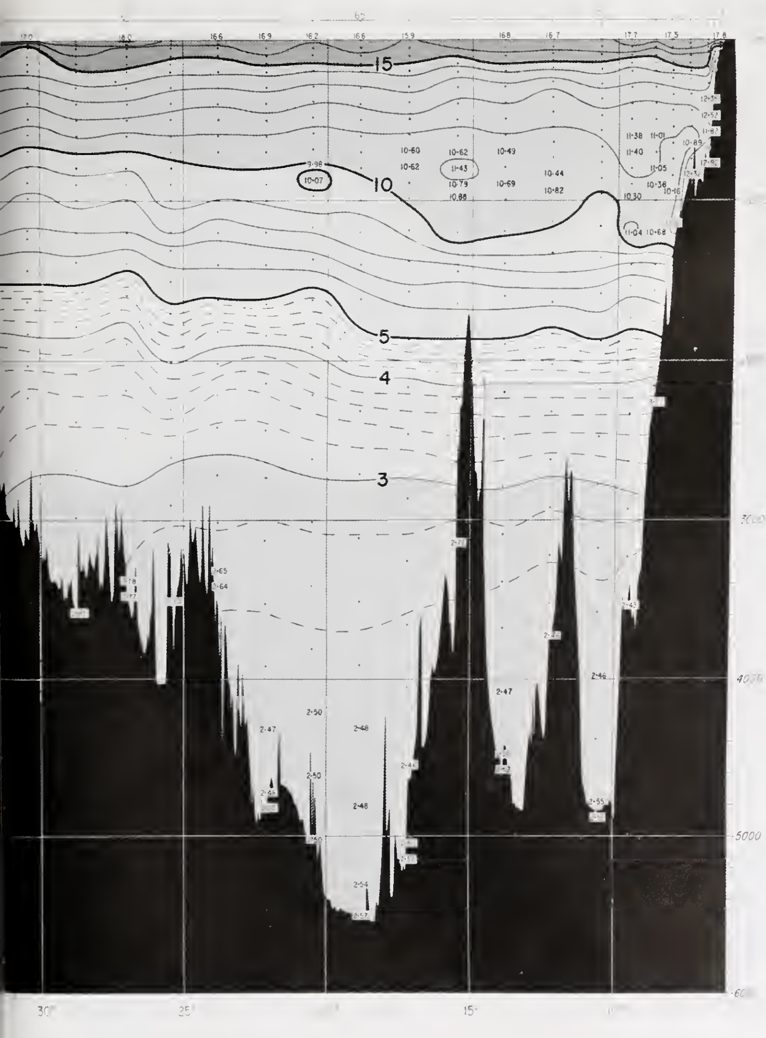
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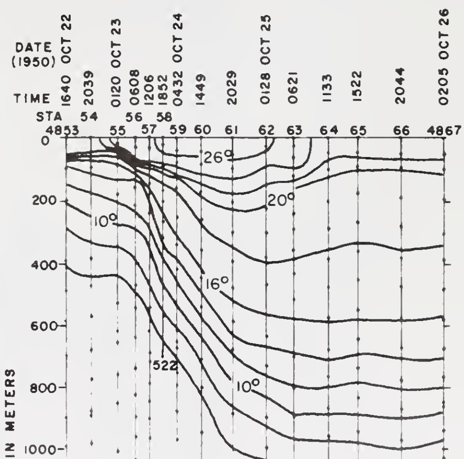
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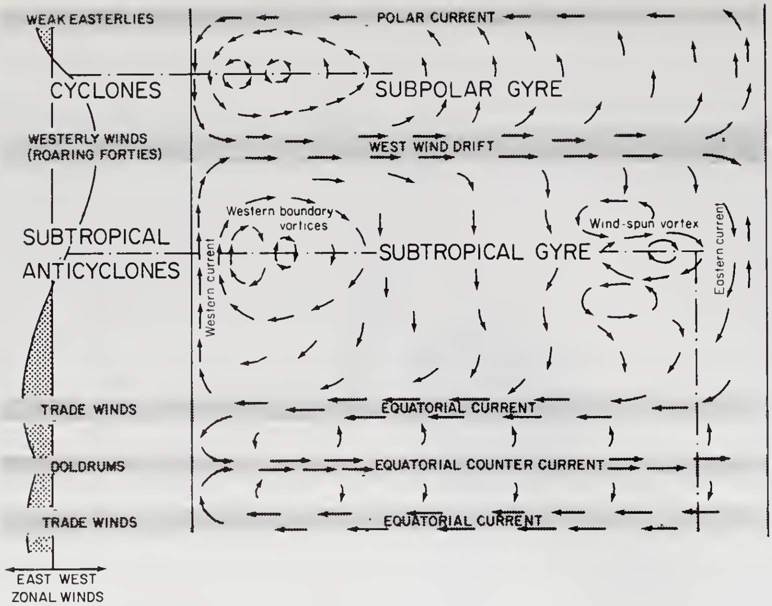

Figure 4. Schematic picture of the circulation in a typical ocean basin. To the left is shown the distribution of eastward and westward winds that are assumed to blow uniformly over the ocean surface. (Adapted from Munk, 1950)

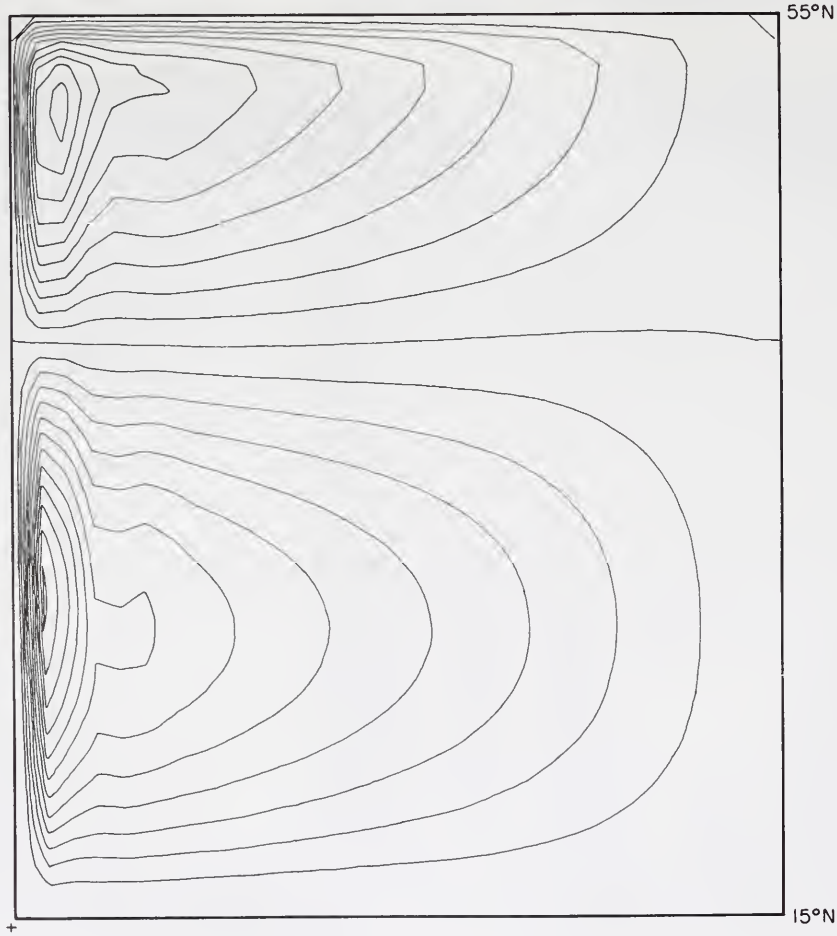

Figure 5. Transport streamline pattern for a model subpolar (top) and subtropical basin. The Gulf Stream is represented by the closely packed streamlines at the western edge (left-hand side) of the subtropical gyre. (Adapted from Han, 1975)

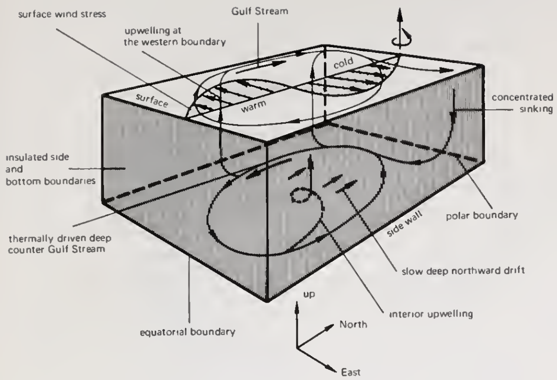

Figure 6. Schematic three-dimensional circulation in an idealized model basin driven by both winds and thermal forces. (Adapted from Bryan, 1975)

off the coast of South Carolina.

The *Aries* expedition of 1959-60, which has served as a key factor in the initiation of the new era of ocean circulation exploration and modeling, was itself motivated to a considerable extent by the desire to test the theoretically predicted slow northward drift of the deep water in the open-ocean region of the North Atlantic (see page 20). The intention was to measure the northward displacement of the position of the center of a cluster of floats, expected to be several hundred kilometers over a period of a year or two. In actuality, the floats were rapidly dispersed in every direction by eddy motions. In the several-year period following the *Aries* experiment, various kinds of evidence slowly accumulated to support the existence of eddies, as requisite technology was developed and theoretical investigations initiated.

Theory and observation go hand in hand. There are so many possibilities in nature that modelers must be guided by real ocean observations. Numerical models explicitly describe oceanic motions down to a certain smallest scale. Smaller scales are not described, but their interplay with the larger-scale flow is taken into account implicitly in a bulk way if it is thought to be important. This is called "parameterization" of the small-scale unresolved flow. For example, the numerical model shown in Figure 5 has a horizontal resolution of only 200 kilometers; that is, values of the velocity, temperature, and pressure are calculated only at a number of points separated by that distance. Smaller-scale motions are parameterized by making the viscosity of the model ocean ten or a hundred times greater than that of seawater. This is done with the assumption that the smaller-scale motions (which in this case includes the eddies because the 200-kilometer spacing is too coarse to resolve them) act to damp out the larger-scale motions. The precise value of the assumed "eddy" viscosity is chosen indirectly. The width of the Gulf Stream in such a model depends upon the size of the eddy viscosity, which is then chosen to give the observed width. The classical models chose a value consistent with the rather broad description of the Gulf Stream provided by the classical data.

The developing technology and increasingly observational activity of the 1950s and 1960s resulted in not only new kinds of measurements, but also measurements taken closer together and more frequently in the ocean. The description of the flow that began to emerge included not just the suggestion of mid-ocean eddies, but a thinner, meandering Gulf Stream, cast-off Gulf Stream rings long-lived in the main thermocline, and a relatively strong, highly variable, transverse flow under the Gulf Stream off the Grand Banks and extending to the south. The first time-series, or long records of current, directly measured from moored current meters provided independent evidence for the existence of the eddies and allowed the first tentative direct estimates of eddy viscosity. In the vicinity of the Gulf Stream, these estimates were negative numbers, indicating that if they could be believed, then the assumed interplay between the smaller-scale motions and the circulation was fundamentally wrong. The damping or amplification of the large-scale motions (general circulation) by the small-scale motions (eddies) is related to the direction in which energy is transferred between the two scales of motion. It lies at the heart of the question of the role of the eddies in the circulation and provides substantial motivation for current experimental and theoretical work.

Considerable research effort is presently directed towards the study of the low-frequency variability of ocean currents involving cooperation between experimentalists and theoreticians, among U.S. scientists from many institutions, together with European and Soviet colleagues. The location of major experimental work carried out in the North Atlantic in this decade is shown in Figure 7. In 1971 scientists from 15 institutions in the U.S., the U.K., and elsewhere decided that ideas and technology were sufficiently advanced and the eddy phenomenon of sufficient potential importance to warrant the undertaking of the first Mid-Ocean Dynamics Experiment–MODE-1 (see page 45). The experimental work that was carried out in the region southwest of Bermuda included an intensive observational period of five months' duration,

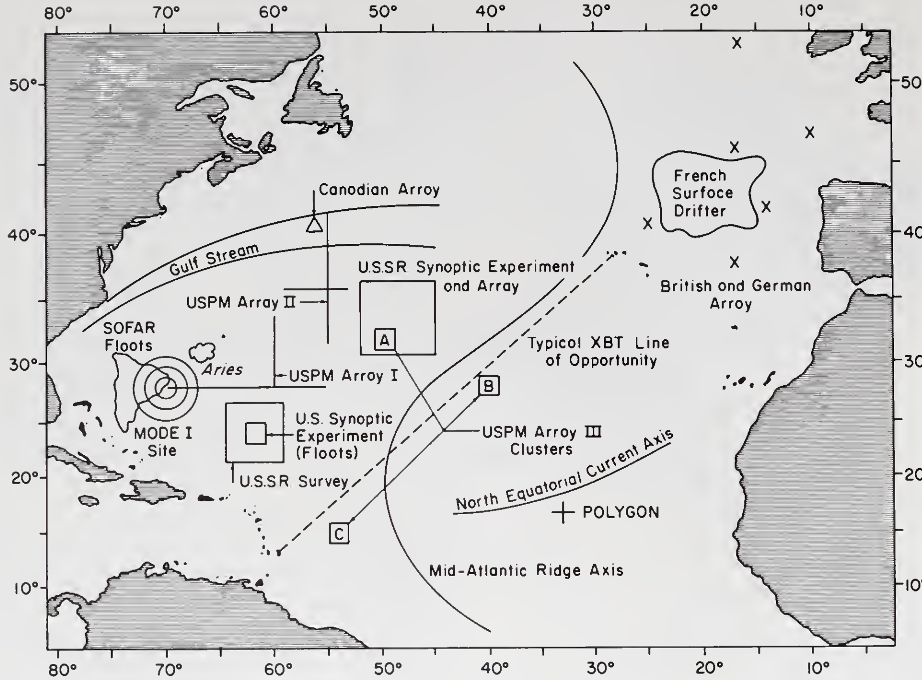

Figure 7. Location of eddy research in the North Atlantic. SOFAR float tracks in the post-MODE-1 drift region are shown in Figure 9. The U.S. POLYMODE (USPM) Array 1 obtained preliminary data from July 1974 to April 1975. USPM Array 2 and the Canadian Array are presently in the water. The other arrays and the synoptic experiments are scheduled to begin in 1977. Many XBT (expendable bathythermograph) tracks are planned not only from POLYMODE ships but also from ships of opportunity from merchant fisheries and other fleets. (Drawing by Nancy Barnes, based on maps by William Simmons)

involving six ships and simultaneous measurements of many features of the eddies by many different types of instruments (see page 54). (The map also shows the locations of the U.S.S.R. moored-current-meter array, POLYGON-70 [see page 40], of the extended U.S. measurements after the end of MODE-1, of instruments presently in the water as part of the initial phase of the joint U.S.-U.S.S.R. POLYMODE program, and of the intended experiments planned for the major intensive year-long POLYMODE effort in 1977-78.)

The existence of the eddy field and its general characteristics have now been definitely established. MODE-1 produced the first synoptic maps ever obtained for a block of the deep ocean (see page 77). The distributions of velocity, density, and pressure, and their evolution in time were obtained with sufficient accuracy so that these data serve as a case history for careful dynamical analysis. We now know the local balance of forces that constrain and direct the eddy flow. Records of current directly measured from moored instruments (Figure 8) show the strong variability field. Long records of current directly measured from modern, long-lived deep floats (Figure 9) now provide the first statistical information about the average amount of energy in the eddy field and how this energy varies in space and time. The picture is sharpening up. Differences in eddy characteristics have been detected from place to place in the gyre that indicate the possibility of significant differences not only in the dynamics of the eddies themselves, but also in the dynamics of the interplay of the eddies and the mean general circulation. Intensive measurements in a few places within the eddy field provide an understanding of the phenomenon that allows the interpretation of eddy signals in less intensive data. The historical data base is being reexamined for clues as to the geographical distribution of the phenomena. New, relatively easily obtained, long sections of temperature in the main thermocline with eddy-scale resolution are being obtained from ships underway as opportunity affords itself (Figure 10). Eddies are found almost everywhere they are looked for and are now known to exist in the North Pacific, Arctic, Antarctic, and Indian oceans.

Theoreticians have made considerable progress in constructing and analyzing models of the mechanisms that govern the dynamical evolution of the eddies themselves, of processes of interaction of the eddies with other scales of motion, and of

factors that could be responsible for the generation or production of the eddies. Because there are several plausible mechanisms, processes, and factors, many models are necessary. The first round of results from these models are now being intercompared. Progress is being stimulated by the increasing number of observations that allow the testing of ideas and lead to the ultimate acceptance or rejection of the models. There are many unanswered questions of a fundamental nature that are now feasible to address. What is (are) the source(s) of the eddies that populate the North Atlantic gyre, how are they coupled to mean flow of the general circulation, and what is their contribution to the physics that controls the general circulation? More specifically, which of the several mechanisms proposed for the generation of eddy energy actually operate in the North Atlantic? Do the eddies drain energy from the mean distribution of currents or of density in the mid-ocean or in the Gulf Stream system, or from decaying Gulf Stream rings? Or does the eddy energy derive from other scales of motion induced in the ocean, for example, by the force of atmospheric storms on the sea surface? Coastal boundaries, and the underlying rough terrain and topography of the sea bottom can cause such energy to convert into motion on the eddy scales. Where in the circulation of the gyre are those crucial regions where the eddies' interplay with the mean circulation is dominant? Do the eddies, on the average, transport sufficient heat, momentum, and energy to influence the large-scale distribution of current, density, and pressure that characterize the general circulation? Future programs such as POLYMODE must define more definitely and comprehensively the distribution of eddy energy and characteristics throughout the North Atlantic gyre and also contribute to the resolution of these critical dynamical questions.

A major achievement has been the construction of numerical models with fine horizontal resolution that explicitly describe eddy-scale motions. These models are useful in assessing dynamical hypotheses, interpreting field data, and guiding the design of elements of the field experiments. Theoretical studies of the general circulation have been carried out in idealized basins in which eddies are spontaneously generated in the flow that is driven only by large-scale steady surface forces, as in the classical models. The difference lies in the fact that the eddy viscosities used are much less than the classical values and the horizontal resolution is much finer. This means that the scales of motion that were parameterized into an eddy

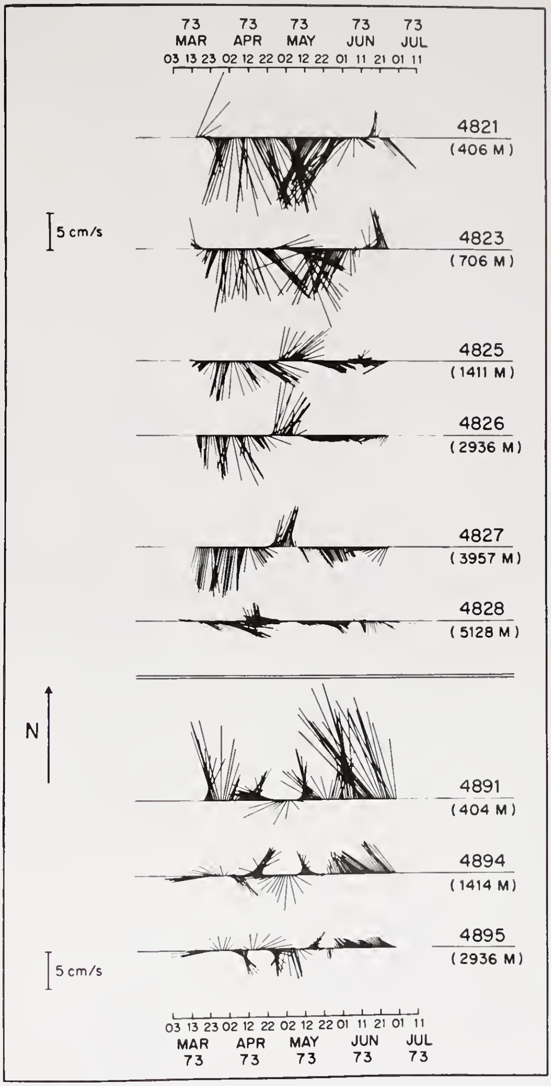

Figure 8. Horizontal velocity versus time as obtained from current meters. Each line represents the 3-day averaged vector obtained from a given meter. The low-frequency oscillations are apparent. (After Schmitz et al., 1976)

viscosity before are now directly resolved and the damping or amplification effect can be computed. This requires a great deal of computer time and stretches the capabilities of the best specially programmed computers we have. Figure 11 is an instantaneous picture of the distribution of transport in the subtropical and subpolar gyres of the same idealized ocean basin as shown in Figure 5, but with the horizontal resolution now increased to 40 kilometers. Averaging the computational results over several years produces the general circulation transport shown in Figure 12, which has strikingly different features from that of the classical model.

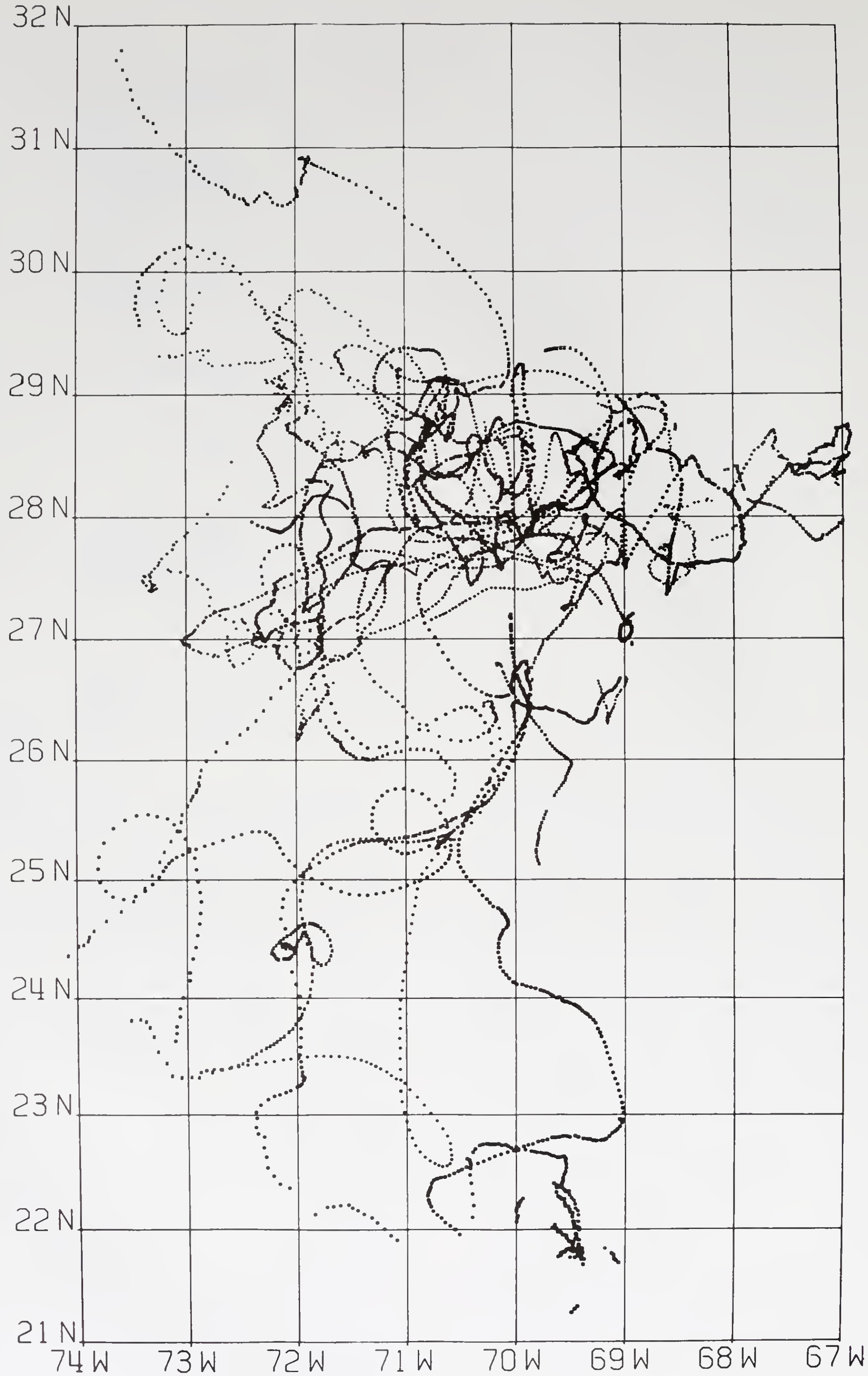

Figure 9. Plot of all SOFAR (SOund Fixing And Ranging) float trajectories from November 1972 through December 1974. Fixes along the trajectories are at one-day intervals, and widely spaced fixes indicate high speeds. Where speeds are low, tracks are more erratic. (After Rossby, 1975)

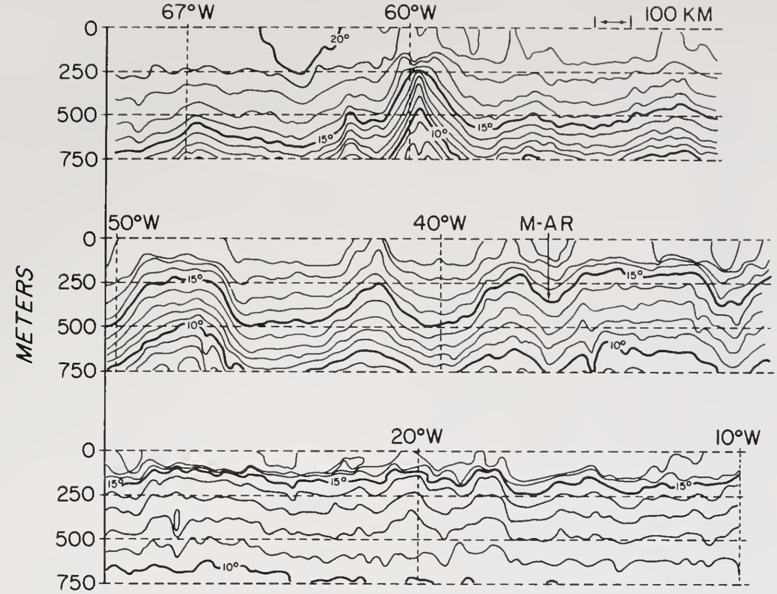

Figure 10. Cross-section of isotherms obtained from closely spaced XBTs (expendable bathythermographs) along 34° 30'N latitude (see page 62). The thermal signal of the eddy field is well indicated and well resolved. M-AR represents the Mid-Atlantic Ridge. (Courtesy of G. Seaver)

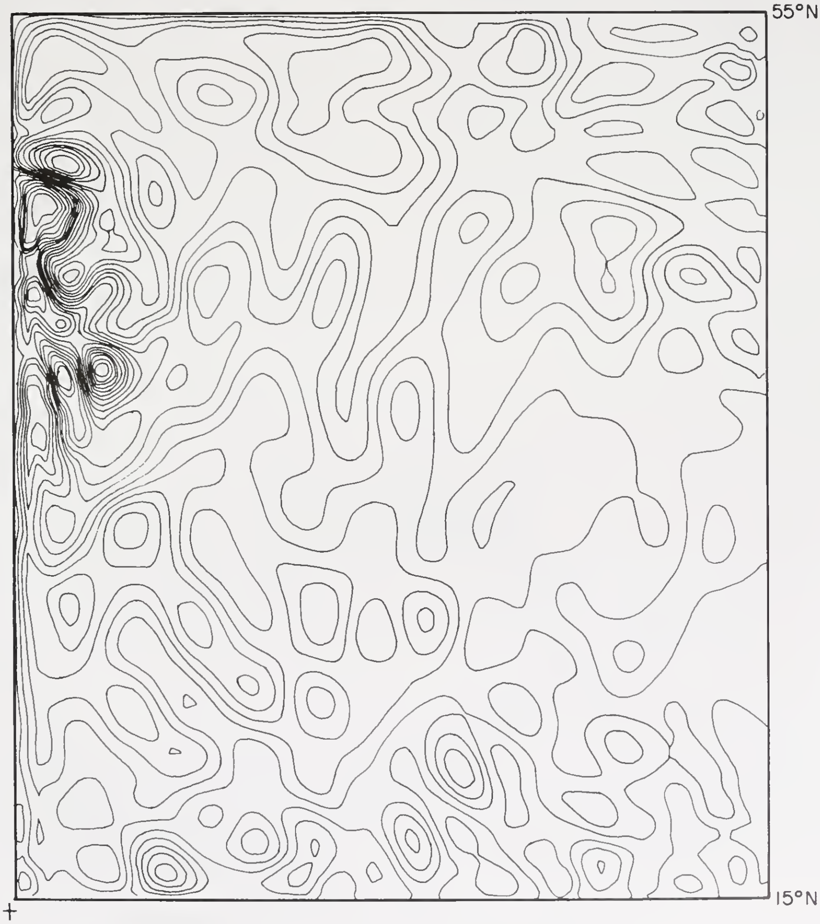

Figure 11. Instantaneous transport streamline pattern for a model ocean similar to that of Figure 5. The wind forcing is the same, but here the viscosity is low and the computational grid is fine (40-kilometer spacing). (Adapted from Han, 1975)

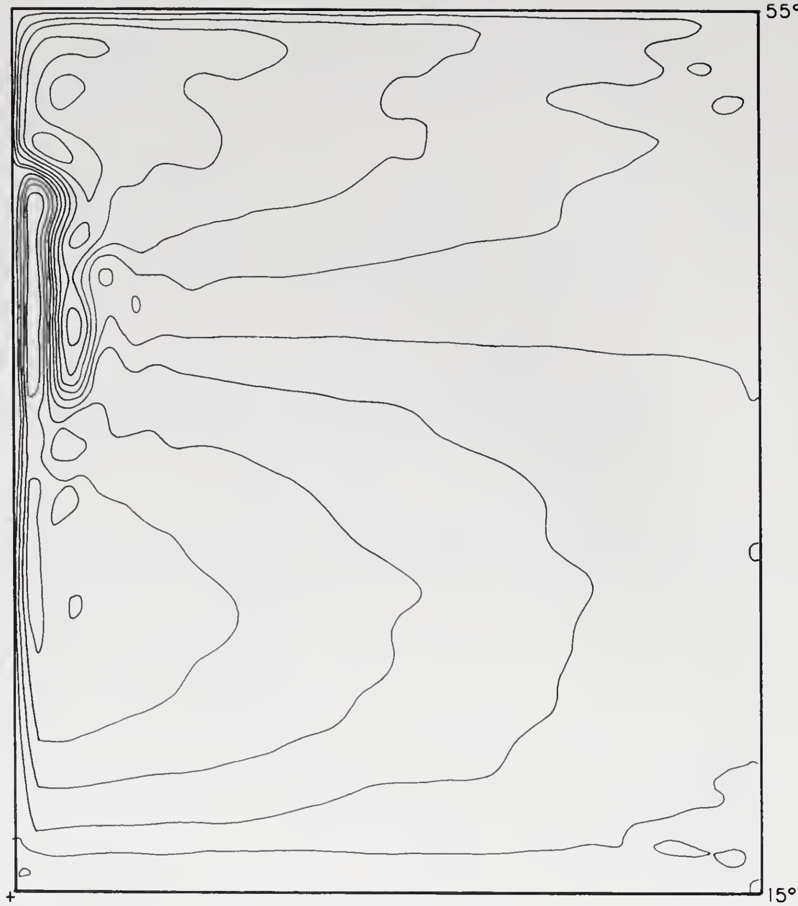

Figure 12. Averaged transport streamlines over several years of computational generated data. (Adapted from Han, 1975)

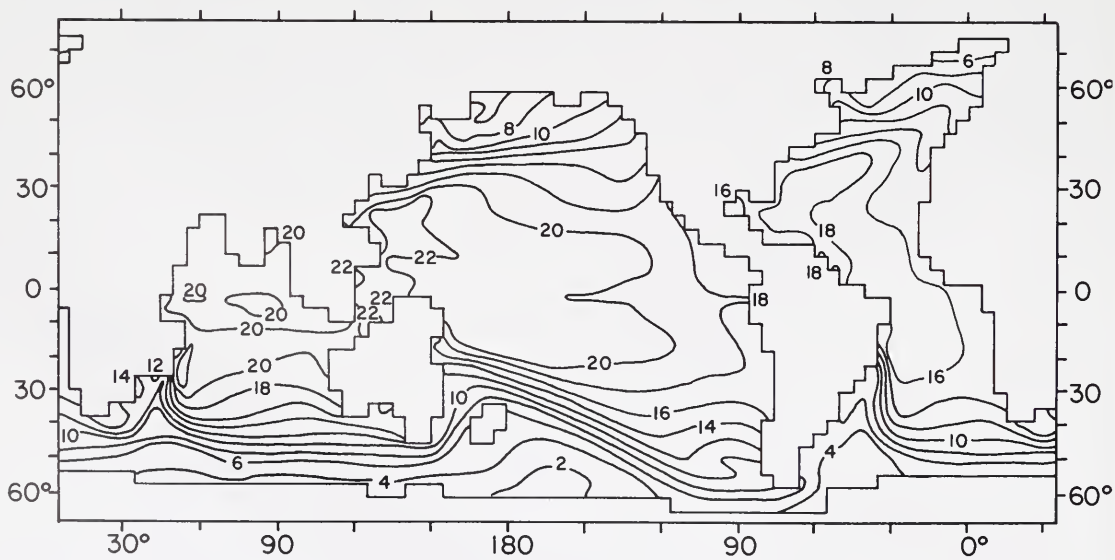

Figure 13. Temperature distribution obtained at a depth of 120 meters from a coarse-grid numerical world ocean model. (After Takano, 1975)

Although in many respects the present models are not yet regarded as accurate physical analogues of the real ocean, they do provide simulated data bases that can be analyzed in terms of the critical dynamical questions. We can answer all of the important questions about the role of the eddies in our numerical ocean. In the example shown, the eddies draw energy from the mean current loop between the subtropical and subpolar gyres and from the mean density distribution in the southwest and contribute significantly to the average heat transport in the southern region of the basin. Performing different numerical experiments corresponding to different conditions of driving forces and different assumptions about the internal dynamics illustrates what the eddies in the real ocean could be doing. Continually comparing the results to oceanic data guides the evolution of the models towards a physically realistic simulation of the real ocean. After the eddy effects are well understood in terms of eddy-resolving high-resolution models, it may be possible to describe the effects of eddies on the large-scale flow implicitly or indirectly, that is to parameterize the eddies and return to a coarse resolution model with a novel internal dynamics replacing the eddy viscosity. Figure 13 shows the temperature distribution obtained in a contemporary numerical model of the world ocean constructed for the purpose of coupling directly to an atmospheric model in order to study the dynamics of climate. Because of the size of the world ocean, and the length of time for which the climate study must be carried out, a large value of eddy viscosity is used and the horizontal resolution is 400 kilometers in the north-south direction and 250 kilometers in the east-west. Notice, for example, how broad the simulated Gulf Stream and Kuroshio currents appear. To be ultimately useful for the study of climate, ocean circulation models must be developed that represent correctly the temperature distribution and transports of heat. If eddy-scale processes are important, they must be either explicitly resolved or physically correctly parameterized, as they occur in the real oceans.

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References

Bryan, K. 1975. Three-dimensional numerical models of the ocean circulation. In *Numerical models of ocean circulation,* proceedings of a symposium held at Durham, N.H., Oct. 17-20, 1972, organized by the Ocean Science Committee of the Ocean Affairs Board, pp. 94-106. Washington, D.C.: National Academy of Sciences. Figure reproduced with permission of the National Academy of Sciences.

Fuglister, F. C. 1960. *Atlantic Ocean atlas.* Woods Hole: Woods Hole Oceanographic Institution.

Han, Y. J. 1975. Numerical simulation of mesoscale ocean eddies. Ph. D. dissertation, University of California, Los Angeles, Department of Meteorology.

Iselin, C. O'D. 1936. A study of the circulation of the western North Atlantic. *Pap. Phys. Oc. and Meteor.,* vol. 4, no. 4.

McLellan, H. J. 1965. *Elements of physical oceanography.* Oxford: Pergamon Press.

Munk, W. H. 1950. On the wind driven ocean circulation. *J. Meteor.* 7:79-93.

Rossby, T., A. D. Voorhis, and D. Webb. 1975. A quasi-Lagrangian study of mid-ocean variability using long range SOFAR floats. *J. Mar. Res.,* vol. 33, no. 3, pp. 355-82.

Schmitz, W. J., et al. 1976. A discussion of recent exploration of the eddy field in the western North Atlantic with a description of *Knorr* Cruise 49. WHOI Technical Report (in preparation).

Takano, K. 1975. A numerical simulation of the world ocean circulation: preliminary results. In *Numerical models of ocean circulation,* proceedings of a symposium held at Durham, N.H., Oct. 17-20, 1972, organized by the Ocean Science Committee of the Ocean Affairs Board, pp. 121-29. Washington, D.C.: National Academy of Sciences. Figure reproduced with permission of the National Academy of Sciences.

Worthington, L. V. 1954. Three detailed cross-sections of the Gulf Stream. *Tellus,* vol. 6, no. 2, pp. 116-23.

Variable

Currents in Mid-Ocean

by J. C. Swallow

To most people an eddy is a current going round in a circle. The Shorter Oxford dictionary defines it as "a circular motion in water, a small whirlpool." But the phenomena that have become known as mid-ocean eddies are small only in comparison to the size of the oceans. Typically they are tens or hundreds of kilometers across. And, while some of them are more or less circular (Gulf Stream rings, for example; see page 65), in other cases the closed-loop pattern is not so obvious. Their common characteristic is that they contain currents varying markedly within the same horizontal scales, of tens or hundreds of kilometers.

Sailors must have noticed eddies in coastal waters almost as soon as they became aware of currents. In mid-ocean, though, nothing was known in detail about surface currents until longitude could be determined accurately at sea, in the second half of the eighteenth century. An English surveyor, Major James Rennell was one of the first to collect reliable observations of surface currents and compile them systematically. His charts and book (*1*) describing currents in the Atlantic were published in 1832, two years after his death. The chapter on the Gulf Stream, written in 1822, included observations of surface currents during seventeen voyages between Halifax and Bermuda, all made within the preceding years after his death. When Rennell wrote his chapter on the Gulf Stream, in 1822, the material that he used included observations of surface currents during seventeen voyages between Halifax and Bermuda, all made within the preceding three years—quite a useful time series, by any standard. Rennell knew that the offshore part of the Gulf Stream varied in latitude and width, and that the variations were not predominantly seasonal. But he could not tell whether the stream was meandering, or shifting laterally as a whole, because he had observations across only one section at a time. He was well aware of the sources of error in his observations and, moreover, of the limitations imposed by their nature. In his own words, "The want of simultaneous observations is an incurable defect. By this we are kept in ignorance of the state of things in every other quarter, save the one in which our *own* observation was made."

The research vessel Aries *on passage to Woods Hole before starting the program of deep-current measurements.*

This defect persisted until the introduction of research vessels, which could make deliberate patterns of investigation. Instead of measuring currents directly, it was easier to observe the vertical distribution of temperature and salinity (which determine density) and calculate relative currents from the density distribution, assuming that the flow was approximately geostrophic (see page 5). In the Northern Hemisphere, a clockwise eddy decreasing in intensity downwards from the surface appears as a depression in the surfaces of constant density, and vice versa. That was how C. O'D. Iselin (*2*) noticed a strong eddy to the north of the Gulf Stream in some of the R/V *Atlantis* surveys of the 1930s. But it was not until new methods were invented for measuring surface currents (*3*) and vertical profiles of temperature (*4*) from a ship underway that anything approaching a true picture of the immediate shape of the offshore Gulf Stream could be drawn. From a detailed multiship survey in 1950, F. C. Fuglister and L. V. Worthington (*5*) showed how narrow and tortuous the track of that current could be, and how eddies might be formed from cut-off meanders.

Despite this clear evidence about the variable nature of a strong surface current and its ability to generate eddies, even in the mid-1950s it was still possible to assume that elsewhere in the ocean the circulation, though weaker, might be relatively less variable. Of course, it was well known that in any hydrographic section there would be irregular variations in the depths of isotherms or density contours, but these irregularities were not usually interpreted as geostrophic eddies. In a paper entitled "Reality and Illusion in Oceanographic Surveys,"

A. Defant (*6*) had shown that, at least in some cases, much of the unevenness in the depths of density surfaces was due to internal tides. Some variability at longer periods was naturally expected as a result of varying winds. As early as 1938, C. G. Rossby made it clear that storms should generate variable currents at all depths in the ocean (*7*): "There is no justification whatsoever for the point of view which pictures the ocean stratosphere as completely inert apart from the slow thermal circulation." However, when G. Veronis and H. Stommel (*8*) estimated that effect quantitatively, they found that "the currents set up in the deep layers are small and are probably no stronger than the slow thermal currents resulting from Antarctic cooling."

When neutrally buoyant floats came into use for measuring deep currents in the mid-1950s, it was hoped that, by observation of the float displacements for a few days or weeks, tidal motions could be averaged out and a start could be made at exploring directly some parts of the deep ocean circulation. Some measurements made in March-April 1957 (*9*) were interpreted as evidence for a deep countercurrent at the western margin of the North Atlantic—which had been predicted in a model of the mean circulation devised by Stommel (*10*).

The first attempt to use neutrally buoyant floats for looking at the structure of deep currents in mid-ocean came in the summer of 1958, in the eastern North Atlantic near 41°N, 14°W. With the floats and tracking method used then, it would have been possible to measure currents, averaged over periods of 2 or 3 weeks, even if they were as small as 1 millimeter per second—the order of magnitude of the mean deep flow, according to some estimates of the deep circulation. The observed currents were significantly stronger than that, and variable in both time and space (*11*). One float, nearly 3 kilometers deep, moved southeast for 3 weeks, then southwest for nearly another 4 weeks, at speeds of 0.5 to 1 centimeter per second. Two floats at 2.5 kilometers depth were tracked simultaneously for 2 weeks. They moved in straight lines and passed within 25 kilometers of each other, but one moved at an average speed of 5 centimeters per second while the other did 0.5 centimeter per second.

No obvious explanation could be seen for these variable deep currents—they did not look particularly wavelike and did not appear to be related to the topography, and the weather had been generally calm. The only possibility that we could think of at the time was that they might somehow be related to the patchy spreading of "Mediterranean water" from its source only 600 kilometers away in the Gulf of Cadiz. It seemed possible that the variable deep currents might be weaker in the Sargasso Sea, where the temperature and salinity distributions were more uniform. That was one reason why the next series of deep mid-ocean current measurements was made in that region in 1959-60 by the research vessel *Aries*.

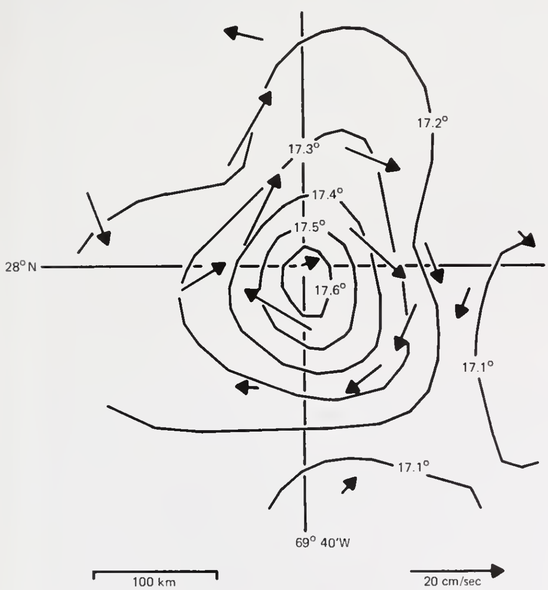
The aim was to track a group of deep free-drifting floats that were designed to have a working life of six months—long enough, it was hoped, so that after two or three such experiments the weak variable motions could be averaged and the long-term mean flow of deep water would be revealed. That was of some interest because Stommel's new model of the deep circulation (*10*) predicted a mean northward flow of deep water there, contrary to the existing idea of a slow southward spreading of North Atlantic deep water. The plan depended critically on the variable currents being weak—if they were appreciably stronger than 1 centimeter per second, it would be difficult to find floats again after the inevitable gaps of a week or so for port calls. As it turned out, variable currents of about 10 centimeters per second were encountered, and the plan had to be changed into an attempt to explore the variable currents themselves. The series of fragmentary pictures that were collected could be summarized as showing eddies approximately 200 kilometers in diameter, increasing in speed downwards (average 6 centimeters per second at 2 kilometers, 10 centimeters per second at 4 kilometers), with a mean westward drift of 2 centimeters per second (*12*). There was some suggestion of a regional variation in strength of the variable currents, depending on distance from the Gulf Stream—the strongest velocities were found northeast of Bermuda, and the weakest to the south. Most of the observations were made near 31°-32°N, 67°-68°W, where the loran coverage was good.

Again, no immediate explanation could be seen for the strong variable deep currents. They seemed to be related to the Gulf Stream, but no Gulf Stream eddies or rings were seen while the *Aries* floats were being tracked. The increase in speed with depth, and a certain tendency for the deeper floats to move nearly north-south, were puzzling features.

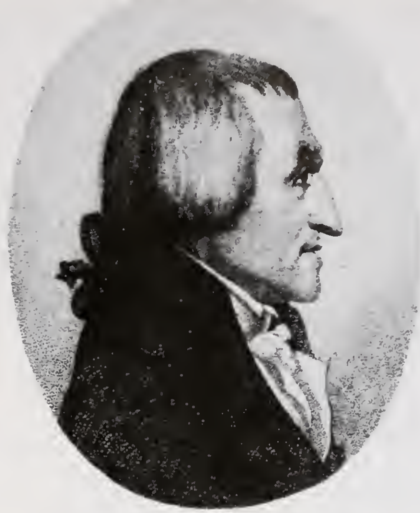
To get any further in exploring these deep currents, new methods of observation were needed that were better matched to the scale of the currents themselves, methods that could provide continuous measurements lasting for many months. spread over an area several hundred kilometers across. Before the *Aries* work ended, W. Richardson (*13*) was already testing the first batch of his recording current meters. The long series of records collected

at site D, between the Gulf Stream and the continental shelf south of Cape Cod, revealed energetic motions at all depths with periods of a few weeks to a few months (*14*). By the early 1970s, moored arrays of improved current meters were being used with confidence for several months at sea. At the same time, T. Rossby and D. Webb (*15*) developed a method for tracking floats at long range from shore-based listening stations. These two techniques have become essential parts of a continuing study of variable currents in mid-ocean, of which MODE-1 (Mid-Ocean Dynamics Experiment) in March-June 1973 was a particularly intense phase of observation (see pages 11, 45, and 77).

A parallel growth of interest in variable currents among oceanographers in the U.S.S.R. can be traced back to a month-long series of currents recorded by W. B. Stockman in the Caspian Sea in 1935. Arrays of moored current meters of increasing size and duration were put out in the North Atlantic in 1958, in the northwest Indian Ocean in 1967 (*16*), and most recently in the tropical North Atlantic in 1970 (*17*). In all of these experiments, most of the effort was concentrated in the upper 1200 meters of the ocean, though some deeper observations were made. Fluctuations of current on a wide variety of scales were detected. In the most recent experiment, known as POLYGON (though the preceding experiments are also referred to as POLYGONs), an array of 17 moorings



A view of the MODE-1 eddy. Isotherms and current vectors near 500 meters depth, for the period April 23-26, 1973. (From the draft synoptic atlas, MODE-1)



James Rennell (1742-1830) joined the British Navy at the age of 14, learned marine surveying, and charted harbors in the East Indies. He then joined the East India Company and in 1764 began a survey of Bengal. He held a commission in the Bengal Engineers, rising to the rank of Major. Badly wounded in 1776, he retired to London, produced an atlas of Bengal, a map of India, and other geographical studies besides his work on currents. (The Bettmann Archive)

200 kilometers across was maintained for 6 months (see page 40). A clockwise elliptical eddy, with axes 90 kilometers and 200 kilometers in length, was seen to move past the array in a westward direction. In the forthcoming POLYMODE (see page 12), the appropriate components of the MODE and POLYGON programs are being combined to provide more extended observations in both space and time. These mid-ocean dynamics experiments have confirmed and greatly extended the earlier results; in MODE-1 the structure of one mid-ocean eddy was examined in detail (see page 77), and much more was learned about the regional distribution of energy in these variable currents at all depths.

Looking back at the *Aries* observations in the light of these more recent results, the original objective of long-term tracking of groups of floats might have been attained by working farther to the south or southeast of Bermuda, where the eddy energy seems to be significantly smaller. But the navigation would have been difficult, and it would have been very dull compared to finding those unexpectedly strong deep currents.

Simultaneously with these developments in the study of variable currents in the North Atlantic, evidence has been accumulating of eddy motions on similar scales in many other parts of the world ocean.

But, before turning to look briefly at some

Positions of eddies and variable currents referred to in the text. The numbers correspond to those in the list of references.

of those observations, perhaps it is appropriate to recall what must be the first report of currents in the region now sometimes called "the MODE area" (see Figure 7, page 12). In the second of Rennell's charts of surface current (*1*), covering the western Atlantic, there is a note at 28°N, extending from 74°W to 70°W: "Currents said to be casual, Sir. Ch. Blagden" (*18*). It would be difficult to improve upon this one-word description of the currents there.

Eddies have been found near most of the major ocean currents. Some of those in the Kuroshio (*19*) and Agulhas currents (*20*) are similar to Gulf Stream rings. The East Australian Current (*21*) seems to be dominated by eddies. The eddy near 6°N in the Somali Current (*22*) is not formed from a meander, but by recirculation of water on the eastern side of the stream. All these eddies in major currents have diameters of tens to hundreds of kilometers and, like the currents themselves, are strongest near the surface. Mostly they have been detected in hydrographic surveys, supplemented by current observations; more

recently in some cases surface temperature anomalies and cloud patterns associated with eddies have been seen in infrared pictures from satellites (*23*). Other eddies of both smaller and larger sizes have been reported near some of these currents—to some extent, of course, what is found depends on the spacing of the observations—but there seems to be no doubt that eddies of various kinds are commonly present near strong surface currents.

Less obvious but similar eddies are found near weaker currents. In the frontal region near 52°N, 20°W in the eastern North Atlantic, a cold-core eddy resembling the subsurface part of a weak Gulf Stream ring has been reported (*24*). Small eddies, about 100 kilometers in diameter, have been seen on at least two occasions in the California Current, and may occur there frequently (*25*). Far below the surface, but still near a well-defined current, a small eddy only 25 kilometers across was found at 1.5 kilometers depth near the deep outflow of "Mediterranean water" at the northern side of the Gulf of Cadiz (*26*). Wavelike patterns of

variable current have been found along the Equator in the Atlantic, in both the westward flowing surface water and in the east-going undercurrent (*27*).

Eddies can be generated when new water masses are being formed. For example, small eddies were seen in a newly formed patch of deep water some 50 kilometers wide and 100 kilometers long, in the northwest Mediterranean Sea (*28*). A subsurface eddy some 150 kilometers in diameter in the Sargasso Sea (*29*), rotating clockwise with a speed of 50 centimeters per second at 400 meters depth, contained an abnormal thickness of "18° water" and may have been generated when some of that water was renewed. Small energetic subsurface eddies (10-20 kilometers diameter, 40-40 centimeters per second maximum speed, 150 meters depth) in the Arctic Ocean may be related to local freezing and changing of water properties, but instability of the neighboring mean current seems a more probable cause (*30*).

Some of the most striking evidence for the widespread occurrence of mid-ocean eddies has come from observations originally made for quite different purposes. From a review of a wide range of bathythermograph sections and hydrographic surveys, R. L. Bernstein and W. B. White concluded that the upper layers of a large part of the central North Pacific are occupied by a mosaic of eddies, with typical diameters of a few hundred kilometers (*31*). While looking for seasonal changes in vertical profiles of temperature from ocean weather ships, A. E. Gill noticed that well below the surface mixed layer, at 250 meters or so, the temperature records were dominated by fluctuations with a period of about 2 months (*32*). A skeptic might wonder how much of that could be due to weather ships changing station at monthly intervals, but the temperature changes seem too large to be due to calibration errors and are interpreted as evidence of eddies moving past the station positions. These results have led to a growing interest in using expendable bathythermographs from ships of opportunity as an economical way of collecting evidence about the distribution of eddies.

Many examples could be quoted of observations that are too widely spaced or too short in duration to reveal eddies clearly but that nevertheless suggest their presence more or less strongly. The northwest Indian Ocean, when surveyed in the summer of 1963, seems likely to have been covered with eddies (*33*), though the sections were too far apart to display them unambiguously. Many short samples of current at various depths, averaged over a day or two, seem too fast and too scattered in direction to represent the mean circulation and are probably fragments of eddies (*34*).

With so much evidence of various kinds pointing to the widespread occurrence of eddies in the ocean, one might well wonder whether there are any places where they do not occur. Certainly they vary in average intensity, across the Sargasso Sea for example, and doubtless in other regions as well. Comparing the irregularity of the 5° isotherm in hydrographic sections across the North Atlantic with the smoothness of the same isotherm in the South Pacific (*35*) suggests that the Pacific really is more peaceful, at least with regard to mid-ocean eddies. And there are variations in the intermittency of eddies; in "the MODE area" and in part of the central North Pacific, they seemed to be close-packed, whereas in the Arctic Ocean they were rarely observed. There seem to be several different kinds of eddies, produced in several different ways, but most commonly their sizes are in the range of a few tens to a few hundreds of kilometers.

The importance of eddies is that they seem to be energetic enough, and sufficiently widespread, to play some part—not yet understood—in the circulation of the oceans. Once again, a quotation from Rennell's work seems appropriate. He classified four kinds of currents: drift, stream, local, and temporary. Most of the mid-ocean eddies would have fallen into the category of temporary currents, which he dismissed in the following words: "It is not the intention to treat of such currents, they being reducible to no rules, and consequently it could answer no useful purpose." If the rules governing these eddies can be discovered, something useful may yet be learned from them.

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References

1. Rennell, J. 1832. *An investigation of the currents of the Atlantic Ocean.* London: Rivington. Contains two charts. Five more charts were published separately.
2. Iselin, C. O'D. 1936. A study of the circulation of the western North Atlantic. *Pap. Phys. Oc. and Meteor.*, vol. 4, no. 4, pp. 1-101.
3. von Arx, W. S. 1950. An electromagnetic method for measuring the velocities of ocean currents from a ship under way. *Pap. Phys. Oc. and Meteor.*, vol. 11, no. 3, pp. 1-62.
4. Spilhaus, A. F. 1940. A detailed study of the surface layers of the ocean in the neighborhood of the Gulf Stream with the aid of rapid measuring hydrographic instruments. *J. Mar. Res.* 3:51-75.
5. Fuglister, F. C., and L. V. Worthington. 1951. Some results of a multiple ship survey of the Gulf Stream. *Tellus*, vol. 3, no. 1, pp. 1-14.

6. Defant, A. 1950. Reality and illusion in oceanographic surveys. *J. Mar. Res.*, vol. 9, no. 2, pp. 120-38.
7. Rossby, C. G. 1938. On the mutual adjustment of pressure and velocity distributions in certain simple current systems, II. *J. Mar. Res.*, vol. 1, no. 3, pp. 239-63. Quotation from p. 259.
8. Veronis, G., and H. Stommel. 1956. The action of variable wind stresses on a stratified ocean. *J. Mar. Res.* 15:43-75. Quotation from p. 74.
9. Swallow, J. C., and L. V. Worthington. 1961. An observation of a deep countercurrent in the western North Atlantic. *Deep-Sea Res.* 8:1-19.
10. Stommel, H. 1957. A survey of ocean current theory. *Deep-Sea Res.* 4:149-84.
11. Swallow, J. C., and B. V. Hamon. 1960. Some measurements of deep currents in the eastern North Atlantic. *Deep-Sea Res.* 6:155-68.
12. Swallow, M. 1961. Deep currents in the open ocean. *Oceanus*, vol. 7, no. 3, pp. 2-8; and
J. Crease. 1962. Velocity measurements in the deep water of the western North Atlantic, summary. *J. Geophys. Res.*, vol. 67, no. 8, pp. 3173-76.
13. Richardson, W. S., P. B. Stimson, and C. H. Wilkins. 1963. Current measurements from moored buoys. *Deep-Sea Res.* 10:369-88.
14. Thompson, R. 1971. Topographic Rossby waves at a site north of the Gulf Stream. *Deep-Sea Res.* 18:1-19.
15. Rossby, T., and D. Webb. 1971. The four month drift of a Swallow float. *Deep-Sea Res.* 18:1035-39.
16. Stockman, W. B., M. N. Koshlyakov, R. V. Ozmidov, L. M. Fomin, and A. D. Yampolsky. 1969. Long-term measurements of physical field variability on oceanic polygons as a new stage in ocean research. *Doklady Akademii Nauk USSR*, vol. 186, no. 5, pp. 1070-73. (English translation NIO ref. T/134)
17. Koshlyakov, M. N., and Y. M. Grachev. 1973. Meso-scale currents at a hydrophysical polygon in the tropical Atlantic. *Deep-Sea Res.* 20:507-26.
18. Sir Charles Blagden (1748-1820) was a friend of James Rennell. There is no mention of observations of currents in that region in his paper "On the heat of the water in the Gulf Stream," 1781 *Phil. Trans.* vol. 71, pp. 334-44, nor in the correspondence between Blagden and Rennell now in the library of the Royal Society.
19. Kawai, H. 1972. Hydrography of the Kuroshio extension. In *Kuroshio: Physical aspects of the Japan Current*, eds. H. Stommel and K. Yoshida, pp. 235-352. Seattle: University of Washington Press.
20. Duncan, C. P. 1968. An eddy in the subtropical convergence southwest of South Africa. *J. Geophys. Res.*, vol. 73, no. 2, pp. 531-34.
21. Boland, F. M., and B. V. Hamon. 1970. The East Australian Current, 1965-1968. *Deep-Sea Res.* 17:777-97.
22. Bruce, J. G. 1973. Large-scale variations of the Somali Current during the southwest monsoon, 1970. *Deep-Sea Res.* 20:837-46.
23. For example, Scully-Power, P., and P. Twitchell. 1975. Satellite observations of cloud patterns over East Australian Current anticyclonic eddies. *Geophys. Res. Letters*, vol. 2, no. 3, pp. 117-19.
24. Howe, M. R., and R. I. Tait. 1967. A subsurface cold-core cyclonic eddy. *Deep-Sea Res.* 14:373-78.
25. McEwen, G. F. 1948. The dynamics of large horizontal eddies (axes vertical) in the ocean off Southern California. *J. Mar. Res.*, vol. 7, no. 3, pp. 188-216; and
J. L. Reid, Jr., R. A. Schwartzlose, and D. M. Brown. 1963. Direct measurements of a small surface eddy off northern Baja California. *J. Mar. Res.*, vol. 21, no. 3, pp. 205-18.
26. Swallow, J. C. 1969. A deep eddy off Cape St. Vincent. *Deep-Sea Res. Suppl.* 16:285-95.
27. Duing, W., and R. Evans. 1975. Long westward waves in the upper Equatorial Atlantic. GATE Report No. 14(1), pp. 310-19.
28. MEDOC Group. 1970. Observation of formation of deep water in the Mediterranean Sea, 1969. *Nature (London)* 227:1037-40.
29. Swallow, M. 1961. Deep currents in the open ocean. *Oceanus*, vol. 7, no. 3, pp. 2-8; and
J. C. Swallow. 1971. The *Aries* current measurements in the western North Atlantic. *Phil. Trans.* 270:451-60.
30. Newton, J. L., K. Aagaard, and L. K. Coachman. 1974. Baroclinic eddies in the Arctic Ocean. *Deep-Sea Res.* 21:707-19; and
K. L. Hunkins. 1974. Subsurface eddies in the Arctic Ocean. *Deep-Sea Res.* 21:1017-33.
31. Bernstein, R. L., and W. B. White. 1974. Time and length scales of baroclinic eddies in the central North Pacific Ocean. *J. Phys. Ocean.* 4:613-24.
32. Gill, A. E. 1975. Evidence for mid-ocean eddies in weather ship records. *Deep-Sea Res.* 22:647-52.
33. Duing, W. 1970. *The monsoon regime of the currents in the Indian Ocean.* Honolulu: East-West Center Press.
34. For example, 41 short trajectories of neutrally buoyant floats mainly at 1 km and 2 km depth in the N.W. Indian Ocean, in G. F. Caston and J. C. Swallow (1972) N.I.O. Internal Reports D9 and D10; or 10 near-bottom current records from the Southern Ocean, in Eltanin Reports (1974) LDGO Technical Report CU-2-74.
35. Fuglister, F. C. 1960. *Atlantic Ocean atlas.* Woods Hole: Woods Hole Oceanographic Institution; and
J. L. Reid. 1973. Upper water and a note on southward flow at mid-depth. *Deep-Sea Res.* 20:39-49, plate 1.

Physics of Ocean Eddies

by Peter Rhines

I am writing this article in Boulder, Colorado, in a university department of astrophysics and geophysics, and yet claim to be an oceanographer. Why? Boulder is a high and dry city, but it contains institutes of atmospheric, astrophysical, environmental, and geophysical research. Within these are some of the finest computers in the country. The relationship between the ocean, our atmosphere, the atmospheres of other planets, and also the behavior of stars and entire galaxies is not so remote as one might think. The most thoughtful statements of how each of these works as a physical system contain elements in common. These are based principally on Newton's laws of motion (modified when necessary to accommodate the theory of relativity), along with equations for chemical, thermodynamical, and radiative changes in the fluids; for example, there are tides in galaxies and gravity waves in the sun, as well as the sea.

An astrophysicist, commenting on these relationships, said recently that the sun was far too close and too visible to be understood. What he meant was that the details of sunspots, granulations, and solar flares tend to overwhelm and confuse the scientists, and to frustrate any simple speculations about how the sun works. If that is so with the sun, what about the ocean at our doorsteps?

It is certainly a difficult task for any one person to assimilate the detail to be found in the maps of temperature and chemical properties of the sea, produced by a century of painstaking effort. And now, in this decade, we have an explosion of ocean observations including, for the first time, abundant *direct* measurements of the currents themselves. Figure 1 shows, as an example, the path of a SOFAR (SOund Fixing And Ranging) float, drifting freely like a balloon, 2000 meters below the surface of the Sargasso Sea. The amazing, looping path follows along the rim of the Blake Plateau and then shoots south to the Antilles Islands, at speeds sometimes approaching 50 centimeters per second—quite fast for the deep ocean. Here one suspects that nearby, cold, abyssal currents, originating in the Greenland Sea, may be responsible for this energetic behavior.

Long before this space-age float existed, the presence of such currents had been inferred from the properties of the water itself (revealing its origin by the high oxygen and tritium content, for example), and from the observation that the water density varies in the horizontal direction. To see this, imagine cold, heavy fluid lying adjacent to warmer, lighter fluid at the same depth; in the presence of gravity this represents an imbalance that can persist only if the water is flowing. The classical procedure was thus to use certain tracers as a historical record of where the water came from, and also to infer the current from variations in the density. But it is not always easy to unravel such a record, any more than one can understand the flow in a coffee cup by looking briefly at the swirls of cream in it—particularly so, if one is interested not only in the paths followed by particular bits of water, but also in the paths followed by *energy*, which moves freely from one mass of fluid to the next. It is this flow of energy that will identify the causes of ocean currents. There are subtleties involved: for example, unusually salty water issues from the Mediterranean into the Atlantic, where it is recognizable thousands of kilometers away. But the flow far from the source is not *caused* by it; rather, the salty mass is swept about by a circulation of more mysterious origin.

The attempt at understanding the balance of forces and flow of energy in the ocean is made

Figure 1. The trajectory of a freely drifting SOFAR float between Miami and Bermuda, at 2000 meters depth. Its path may be related to the shape of the sea floor, and to the occurrence nearby of strong abyssal currents. (Courtesy of T. Rossby and D. Webb)


31 N
30 N
29 N
28 N
27 N
26 N
25 N
24 N
23 N
77 W
76 W
75 W
74 W
73 W
72 W
I
II
III
IV
V
VI
VII
7
14
21
28

difficult by the variability of the currents; that is, by the eddies. The currents are in fact far too capricious to be mapped once and for all, so that the procedure of the classical oceanographer—the gradual filling in of a jigsaw picture of the ocean—may simply not work. We hope we will not fall into the astrophysicist's quandary and give up our theoretical dreams entirely in the face of this detail. But, one must admit, there are few whose minds can encompass the entire range of ocean lore. At one extreme, oceanography may involve many separate measurements that fit no obvious pattern and, in addition, contain some instrumental error. At the other, it may include no observations at all, but instead be an intricate and abstract mathematical theory, one whose relevance to the true ocean is unknown. To span this distance, there is a kind of scientific bucket brigade, carrying observations and notions of the sea from hand to hand, in the direction of the fires that rage in the minds of the mathematicians, who talk endlessly about "turbulence." But, at the same time, the buckets do not return empty. Now and then there appears an ethereal construct that is of some aid to the sea-going experimentalists.

Somewhere in the middle of this line connecting the practical with the abstract is a new and important unit, the computer experimenter. Not long ago, this person was absent, and unnecessary. There were then just a few theoretical oceanographers, and they managed remarkably well to do mathematics and also to work at sea. Then, there was not so much to think about; the burden of truth was lighter. Now, the compendious memory and the speed of modern computers are indispensable.

Slow-Ocean Models

The first theories of ocean currents and density fields were linear. Restricting ideas to the wind-driven part of the flow, theoreticians imagined the ocean to contain an average current pattern that is solely the result of the average winds. On top of this, the time-varying winds (for instance, the stronger winds of winter, and the routine passage of cyclones and anticyclones) add patterns of time-varying currents to the mean flow. This is rigorously correct if the driving winds are weak enough. One might imagine a set of identical oceans blown upon by winds of the same spatial pattern, and time variation, but of different intensity. In the most weakly driven of oceans the flows will be very slow and will obey the relatively simple linear theory. There, the currents respond separately to each component part of the driving winds, and each part can be understood independently of the others. The intensity of the currents would vary directly with the intensity of the wind. In none of the strongly driven oceans, however, would such simple rules prevail.

The "slow" oceans of this set have eddies in them: cells of rotating current wax and wane. But, in fact, *weak eddies are waves.* This is so if we generalize the notion of waves to include oscillatory motion within the body of a medium in which flow patterns, often sinusoidal ones, travel great distances while the fluid itself moves only to and fro. These are horizontal waves, analogous to sound waves in air, water, or a solid object. They are known as Rossby waves after the Swede who postulated their existence—not in the ocean, but in the atmosphere. Waves, by definition, require a force to restore to the equilibrium position a parcel of water displaced from that position. Here, in the simplest case, it is the horizontal Coriolis force (produced by the earth's rotation) and its dependence on latitude that tends to bring water back once the water is displaced in latitude. The beauty of the slow oceans is that the fate of energy put in by the shifting winds can be followed and is largely independent of the mean currents.

Before moving on, let us look at some of the properties of the slow, linear ocean model, for this model resembles the faster ones to be developed later. The surface circulation of the North Atlantic, in the slow-ocean model, is a large, central clockwise flow bounded in the south by equatorial currents. The northward branch of flow is bunched up at the western boundary, forming the intense Gulf Stream, which is returned southward by a broad flow filling the remainder of the ocean. The narrowness of the Gulf Stream is now a well-known signature of the *beta effect,* or that same combination of Coriolis force and earth's sphericity that permits Rossby waves to exist. Here, in the model North Atlantic, the clockwise sense of the wind stress favors southward flow, and the water can return to the north only in the "shelter" of the western boundary. In a beautiful mathematical theory begun by Stommel, the Gulf Stream appears as a boundary layer, rather like the region very near an airplane wing where fluid velocity varies unusually quickly from streamline to streamline. The average circulation in this model is thus far different from that which would occur in a world without land masses; the fluid would prefer to circulate swiftly around latitude circles (like the atmosphere itself) but is prevented from doing so by the continents.

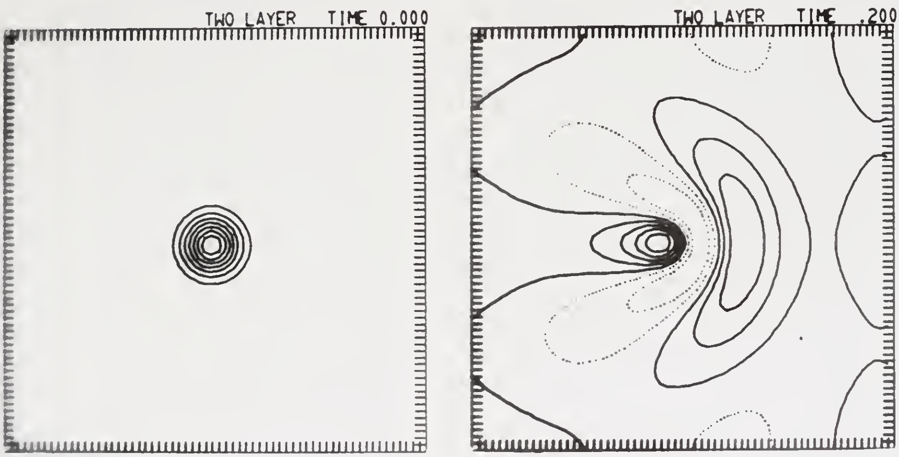
The significance of the fluid boundaries does not stop here. The waves (or "slow" eddies)

are themselves intensified at the western rim of an ocean. Both kinds of intensification may be viewed as a result of laws governing the amount of spin, or shearing motion, within a fluid. It is found that energy present at a western boundary leads to increasing amounts of spin there, while, conversely, energy at eastern boundaries of an ocean causes the net spin to decrease.

In a slow ocean, all time-variable currents can be thought of as combinations of Rossby waves. Let us for the moment look at another simulation, one designed as a simple demonstration of the properties of these waves. Imagine setting loose a single, 200-kilometer-wide circular eddy in the middle of an otherwise quiet ocean. This is done (by computer) in Figure 2. Without the beta effect, the fluid would merely circulate slowly along the streamlines, which themselves would not change. But here the initial pattern bursts into Rossby waves. The waves are lopsided in favor of westward propagation, so they tend to carry their energy and spin to the western boundary, there to accumulate.

In the general model of a slowly moving ocean, the circulation is, at any point, the result of a global pattern of winds. The simulated ocean responds as a whole, and must be understood as a whole, rather than viewed with some local relation between wind and net flow in mind. And it is the Rossby waves that are the messengers carrying the information about distant winds. In a similar sense, vibrational waves in a solid distribute stresses imposed by some outside force, and gravity waves in a shallow pan of water that is suddenly tipped up, carry a pulse of flow across the pan, readjusting the free surface to the new horizontal position.

This collaboration between waves and circulation seems to occur in a particularly coordinated way in the western Indian Ocean. There, the winds turn abruptly northeastward in the spring, as the Asian monsoon strengthens. The



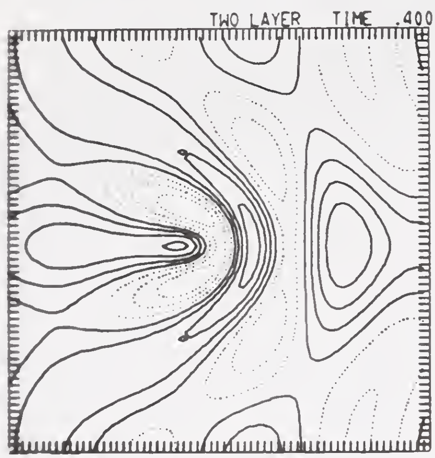


Figure 2. A time sequence of the development of flow patterns in a slow-ocean model. In each picture the current is directed along the streamlines depicted. Streamlines describe the motion of a given volume of fluid over a given area at a particular moment. The net flow between any two streamlines is the same. Where the lines are far apart, the flow is slow; where they are close together, the flow speeds up. You are looking down on the ocean surface, which is a region 2000 kilometers square. Initially the flow is concentrated in a single round eddy. It would remain there forever, but for the earth's spherical shape, which permits Rossby waves to carry the energy about. Time is in months. This and succeeding computer models were carried out at the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

ocean most likely responds to this sudden wind shift by developing Rossby waves that carry the signal of the mean circulation from the open ocean to the western boundary. After a few weeks, the Somali Current (the analogue of the Gulf Stream) is well established.

With regard to the vertical distribution of current in the waves and circulation, there are strong currents in the upper ocean associated with the topography of the pycnocline, and also a current uniform with depth, that is, independent of it. (The pycnocline is the surface that crudely separates the heavy abyssal water from the less-dense surface water.) In a linear model these two modes of current, associated with Rossby waves, can be treated independently, and each propagates with its own natural wave speed. The former, or baroclinic mode, is very slow moving, perhaps 2 kilometers per day at middle latitudes. The latter, or barotropic-mode Rossby wave, is faster, ranging from perhaps 5 to 10 kilometers per day for the wavelengths of interest here.

Faster-Ocean Models

We now know that the currents in the real ocean are not slow enough to be dealt with entirely in terms of the linearized models discussed above. Consider first the time-varying currents or eddies. Slowness, at the very least, requires the speed at which the water is actually moving to be below the speed at which the wave pattern moves. Since these propagation speeds are only 2-10 kilometers per day, they are exceeded by those of the currents in many parts of the ocean. When this happens, nonwavelike and nonlinear effects are produced—effects similar to those observed in surface-water waves and sound waves. Steep surface waves break and create all kinds of chaos not accounted for by wave theory, and loud sound becomes distorted. We must expect eddies to do the same. Second, the circulation, as well, changes character in the presence of realistic wind stresses. The Gulf Stream, instead of smoothly losing its fluid to the open ocean as it moves northward, escapes the coast altogether. It is a mathematician's nightmare, with the boundary current escaping its boundary, and snaking around the open ocean like a fire hose out of control.

Our hope that this chaos might still act somewhat like a slow ocean is based on a notion of miniaturization. If the ocean were shaped like a teacup, and one stood far away, shouldn't its flow look just like the flow in a real teacup? What effects does a change in scale produce? Very important ones if the viscosity (the internal damping qualities) of the fluid is not changed commensurately. Primarily, increasing the size of a flow means that the smoothing effect of viscosity is weakened, and thus the flow can be more complex or turbulent, with eddies of many different sizes.

Now, for lack of a theory of turbulence (utterly confused fluid flow), it has been customary to assume that the smaller eddies in a large-scale flow act to augment the viscosity. In the simplest situations this is certainly true. Eddies can carry energy and spin about, acting to spread out concentrated jets of flow, as does the viscosity. But recently it has been realized that the flow must be fully chaotic in all three dimensions—up and down, east and west, north and south—to act this way. In the ocean the fluid generally is constrained by the density gradients to move nearly horizontally, with little upward or downward displacement. Thus complete chaos is impossible, and we have had to start afresh with a study of the partial chaos that results when fluid moves about freely in the horizontal, but with only slight vertical motion.

The Appearance of Computers

The wave patterns for the slow-ocean model (Figure 2) were in fact quite well known before the day of efficient computers. One is used here to draw the pictures. But in the faster-ocean models the prediction equations simply cannot be solved with pencil and paper alone. Some important ideas about eddies existed long ago, but without our being able to see them realized in an experiment, we were lacking in conviction about them. In the 1950s, laboratory models, involving rotating basins of water, were a particularly important testing ground for ideas and a stimulus to the theory.

Nowadays we take the insoluble mathematical equations governing ocean currents and make use of the following crucial fact: although nonlinear equations cannot be solved to predict flows far into the future, they can always be solved for a brief instant to predict, say, what the large-scale water flow will be like two hours hence. They are simply extrapolated, and the errors are small if the time interval is short. Of course, there will be very little change during this period of time, so the answer is unexciting. But give it to a computer, which will step forward making this same calculation thousands of times, and you will have a prediction for next year.

This was a scheme envisioned in the early part of this century by the English meteorologist L. F. Richardson who wanted to solve these same equations to forecast weather. Lacking a computer, Richardson fancifully described an institute in which there was a giant hall. In this hall 64,000

technicians worked by hand to extrapolate the equations forward into the future, step by step. Of course this institute would have had some difficulty in keeping up with the weather itself. But the continual interest of men like Richardson over the decades has been one of the strongest incentives to the design of the modern computer.

The analogy between weather forecasting and our studies of ocean currents breaks down eventually. There are errors in this procedure of numerical integration, and they become worse for long-range forecasts. The measure of success in forecasting is the prediction of the weather at a given place and time, and yet this is not the primary goal of studies in ocean dynamics. We are more interested in the average shapes and sizes of eddies, the long-term movements of the water across the globe, and the flow of energy from its sources to where it is lost to fluid friction. The difference between these two sciences is rather like the difference between medical research and psychology. The understanding of the inner workings of the body, though great, does not allow us to make behavioral predictions.

The simulation of oceanic flows with high-speed computers is a step forward from the linear theory, but it still moves us only part of the way toward the "fast" oceans. The best computer we have is just able to simulate an actual teacup of eddies, and so we must still rely on miniaturization assumptions to scale the answers up to the ocean. But at least the computer can handle the strong kind of nonlinearity, or partial chaos, that is present in all but the smallest and most viscous of model oceans.

Earlier, a simple ocean model was used in a discussion of the properties of propagating waves. Now, with the use of a computer, the properties of faster, nonlinear, time-varying currents will be examined. Figure 3 is an idealized experiment in which a quiltlike pattern of eddies is started off and allowed to evolve freely. The difference from Figure 2, other than the number of eddies, is that the current speed along the streamlines is now much greater. The succeeding pictures show that, remarkably, the small eddies have coalesced to form a few lazy gyres. This is just the reverse of the result for totally chaotic, three-dimensional turbulence in which energy is degraded into smaller and smaller eddies until ultimately being lost to viscous smoothing. In fact, if one calculated the effective viscosity that the smaller eddies exert on the larger ones, it would be negative. Clearly the ocean is not a teacup, and energy put into eddies and intense currents cannot simply flow out of the system into miniscule eddies and thence be dissipated by viscosity. The Gulf Stream, after it leaves the Straits of Florida, does not spread out as would a jet of fluid in a laboratory experiment. Instead it seems to remain narrow and intense, until finally breaking apart in mid-ocean.

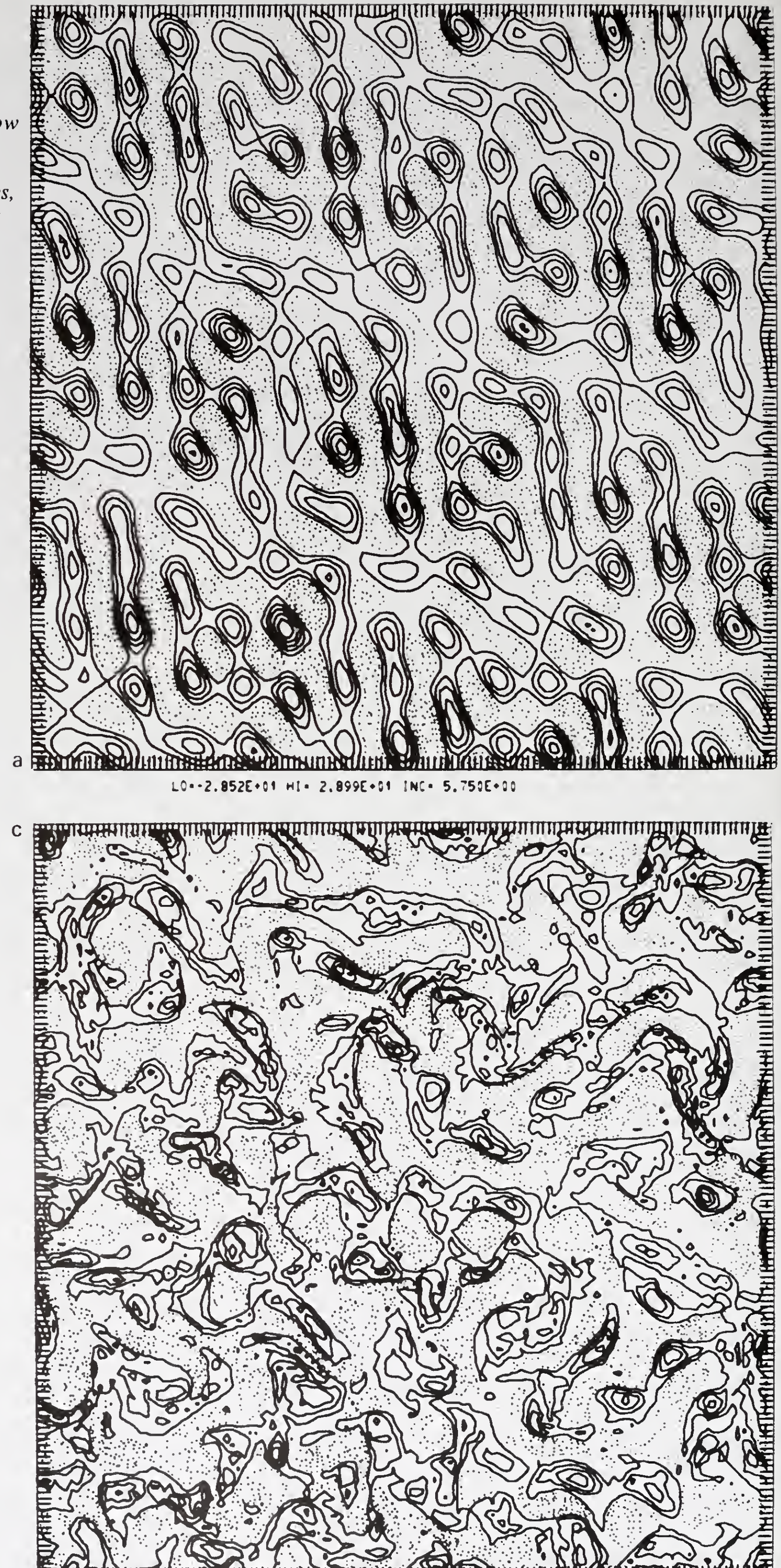
Types of Eddy Motion

Figures 2 and 3 describe two widely differing species of eddies: the first the simple linear Rossby waves, the second a kind of two-dimensional turbulent flow. In the real ocean, in many instances, eddy motion combines the properties of both species, and computer simulations can be made in which properties of both limits are visible. Figure 4 shows a space-time diagram of the currents along a particular latitude line, both from a computer simulation and from the ocean. The inclined attitude of the contour lines suggests that eddies propagate westward (just as in the simplest waves) in theory and in fact.

The discussion above is relevant to the barotropic mode of current and therefore says little about the intense surface eddies, or the pycnocline ridges and valleys. These baroclinic eddies have also been verified, by several groups of observers, to propagate westward, even when the current velocity is very strong. This is one example (the very existence of the Gulf Stream in fast oceans is another) of a theoretical prediction holding partially true, far beyond the strict limitations on its validity. I say partially because the two modes of eddy actually interact with one another in fast oceans. Yet the use of the linear approximation still has provided very useful idealizations of observed eddy patterns.

In neither of the above cases do individual eddies have any particular identity. Energy passes by jostling freely from cell to cell. The same is true with surface waves moving towards a beach; one tries to follow an individual wave crest, and it soon disappears. The energy in this analogue moves at only one-half the speed of the wave crests. But a third species of eddy does exist in the ocean. It is the "lone eddy" or "ring," of the kind seen to be cast off by the Gulf Stream (see pages 65 and 69). This circular flow is intense, greater than a meter per second, in the core. This example, which oceanographers seem most fond of, is often thought to be the typical eddy. In fact, it is the supernova of eddies and retains its uniqueness (the energy stays within the same patch of water) for longer than a year. One such ring may be seen in the computer simulation in Figure 5. After some time, it is likely that the Gulf Stream rings begin to radiate Rossby

Figure 3. A time sequence of the evolution of a field of eddies in a fast-ocean model. Initially very small, the eddies coalesce into bigger and bigger flow patterns. This is a consequence of the turbulent nature of the currents. Here the presentation is not one of streamlines, but of patterns of dye that is swept about by the fluid.



b

LO=-7.569E+00 HI= 7.065E+00 INC= 1.463E+00

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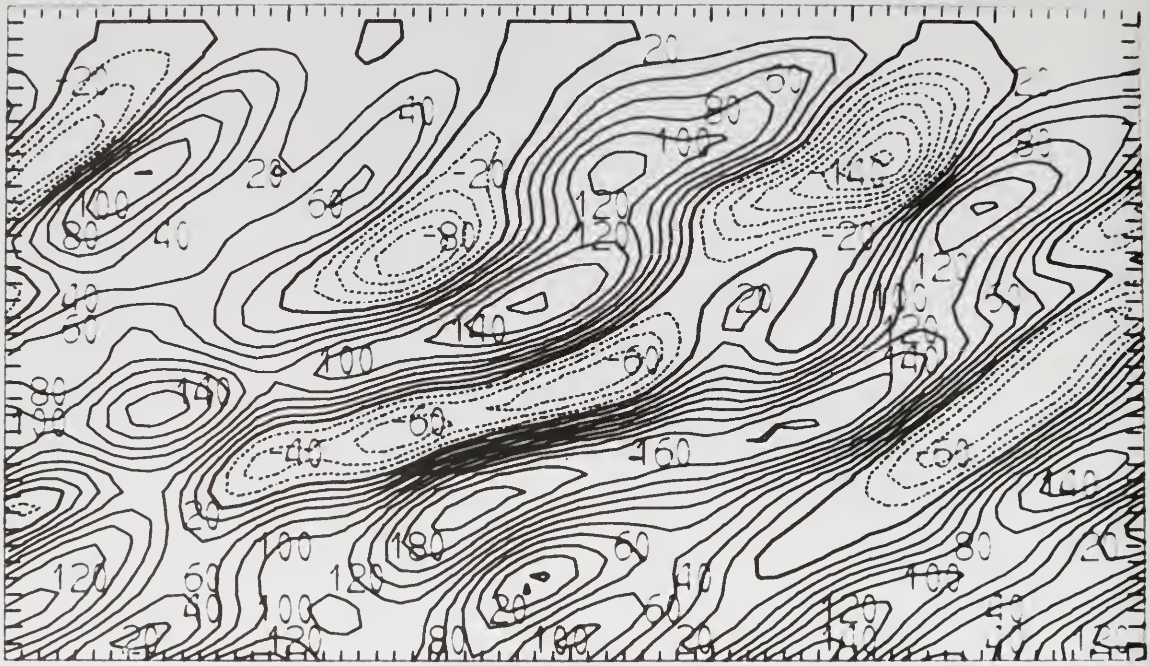


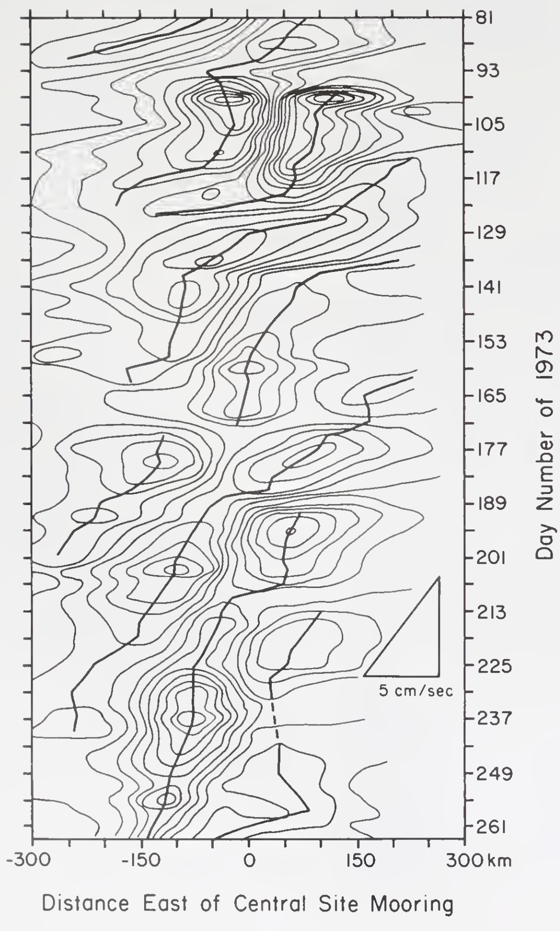


Figure 4. (Top) Space-time plot of eddies in a computer simulation. The horizontal axis is east-west coordinate; the vertical axis is time, increasing downward. Thus we are seeing the movement of particular streamlines along a latitude line, with time. The inclination of the patterns indicates a westward movement, not of fluid but of wave-crests. (Bottom) A diagram similar to the one above but based on actual ocean currents in MODE-1 (Mid-Ocean Dynamics Experiment). Westward propagation again appears.

waves and excite the deeper water into motion. In doing so they may produce some of the lower-level chaos seen far from the Gulf Stream.

A fourth kind of eddy motion, shown in the computer simulation in Figure 6 is simply the meandering motion of a thin jet of current like the Gulf Stream. It is useful in this instance to consider the flow as the sum of the time-averaged (mean) circulation plus the time-varying part (eddy motion). The mean circulation is much broader than the jet itself. The eddy motion will appear as elliptical cells of flow that account for the meandering motion. This sounds like a semantic exercise, but it is useful to lump together all unsteady currents and call them eddies, and ascertain their effect on the time-averaged flow pattern. However, these meanders have a special physics describing them; they are produced by the instability of the "polar" front that lies between the warm and cold regions of the sea. Yet there is some similarity between their behavior and that of quiltlike patterns of eddies. An important driving force is the tendency of heavy,

Figure 5. The shape of the temperature distribution for the experiment shown in Figure 6. The Gulf Stream separates cold water, to the north, from warm water, to the south. As it meanders, a cold eddy breaks off and wanders to the south.

cold water in the north to displace lighter, warm water at the same level in the south. This same desire of the fluid to come back to equilibrium is active in any array of baroclinic eddies. The theory for this process quite accurately predicts that eddies of 100-200 kilometers in diameter should appear, and this is a partial rationalization of the observed size of eddies.

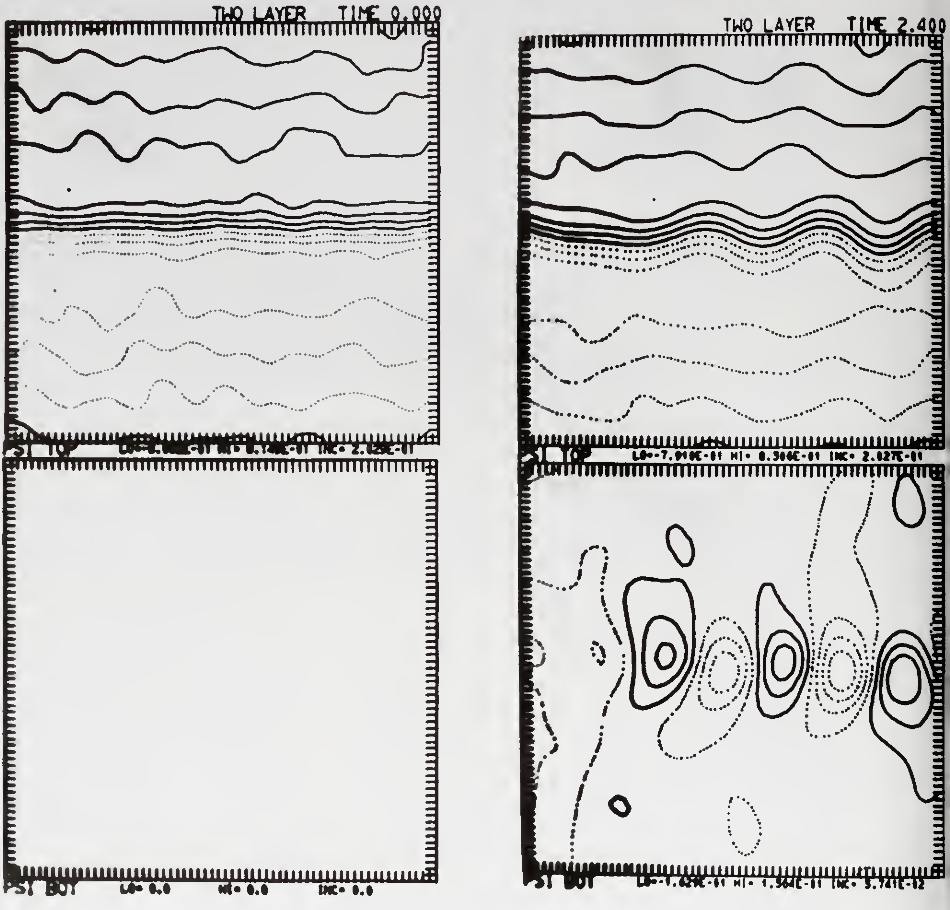
A fifth, and my final, example of eddy motion is the most difficult to describe mathematically. This is the simple tendency for a rough sea floor to break up currents into little eddies. The effect is amplified by the earth's rotation, which tends to pull the flow at different depths into vertically coherent alignment. A typical representation of the hills and valleys of the sea floor, used in my simulations, is shown in Figure 7. Free currents can flow easily along contours of constant height, but waves result wherever fluid is forced to move across these same contours. Figure 8 shows the flow in a computer simulation of the deep ocean, over a typical pattern of seamounts and ridges. The increasing complexity and small size of the deep eddies are evident.

When all of the important features of the ocean are put into the theories or simulations of ocean eddies (density stratification, beta effect, mean currents, wind stress, rough bottom topography, for a start), one finds emerging various hybrids of the above special examples. But it is comforting that, despite a great deal of variation from place to place in the ocean, the predicted eddies resemble the 200-kilometer-wide cells seen at sea. And, what is most amusing, none of those features can be omitted without making the simulated patterns grossly in error.

Interaction Between Eddies and Circulation

Waves on the Gulf Stream front represent one genuine interaction between eddies and the time-averaged flow (otherwise known as the Eulerian circulation); here the circulation produces eddies. But the events can also work in the opposite direction, for eddies, if fast enough, can gang up to drive a systematic flow. It is just possible that the ocean works as a sort of Rube Goldberg device, with the wind driving a strong circulation that breaks down into eddies; the eddies then drift off and radiate into the far reaches of the ocean, where they recombine to drive new elements of circulation. Models of this sort are now being explored. Some rigorous theory suggests that, indeed, the chaotic stirring ability of eddies (which would quickly diffuse a huge blob of ink) induces, by necessity, a circulation of the sea at the next larger scale.

Figure 6. *Streamline patterns in a computer model of the Gulf Stream. The upper sequence shows the upper-ocean flow, the lower sequence shows the flow in the deeper water. The current, initially narrow and intense in the upper water, and nonexistent in the deep water, begins to meander, and spontaneously breaks into a pattern of eddies, in both deep and shallow water. Time is in months.*



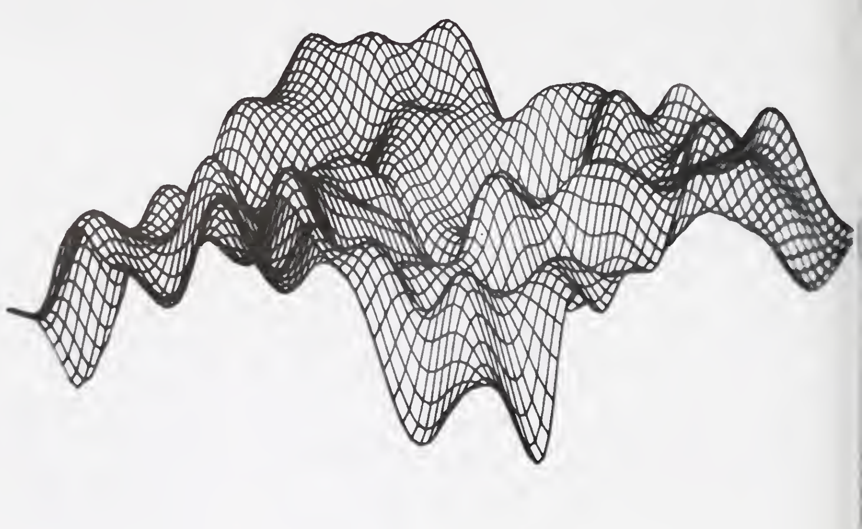


Figure 7. Perspective view of the sea-floor topography used in simulations of ocean eddy fields. The region is 2000 kilometers square; consequently, much small-scale detail had to be deleted from the model.

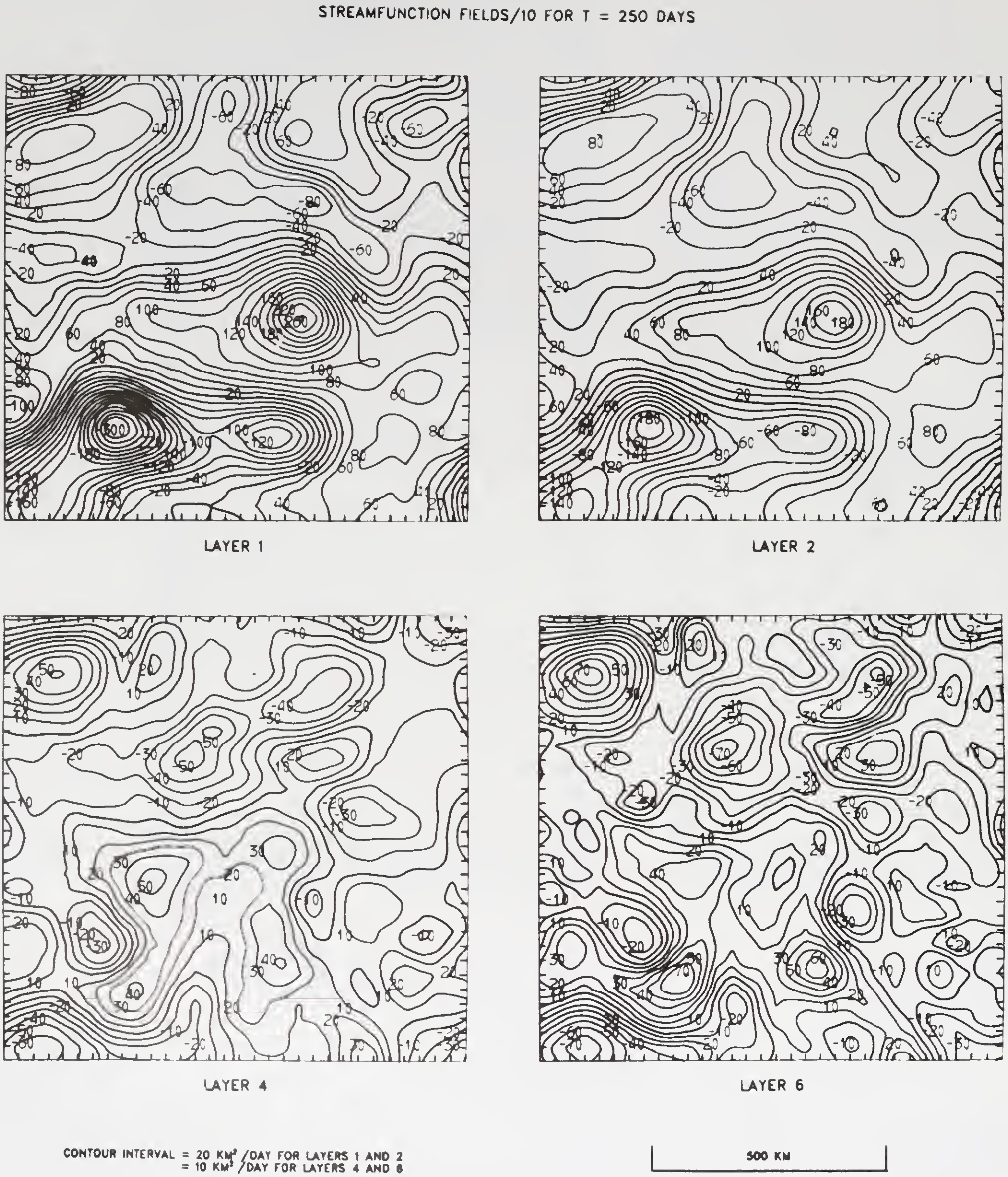
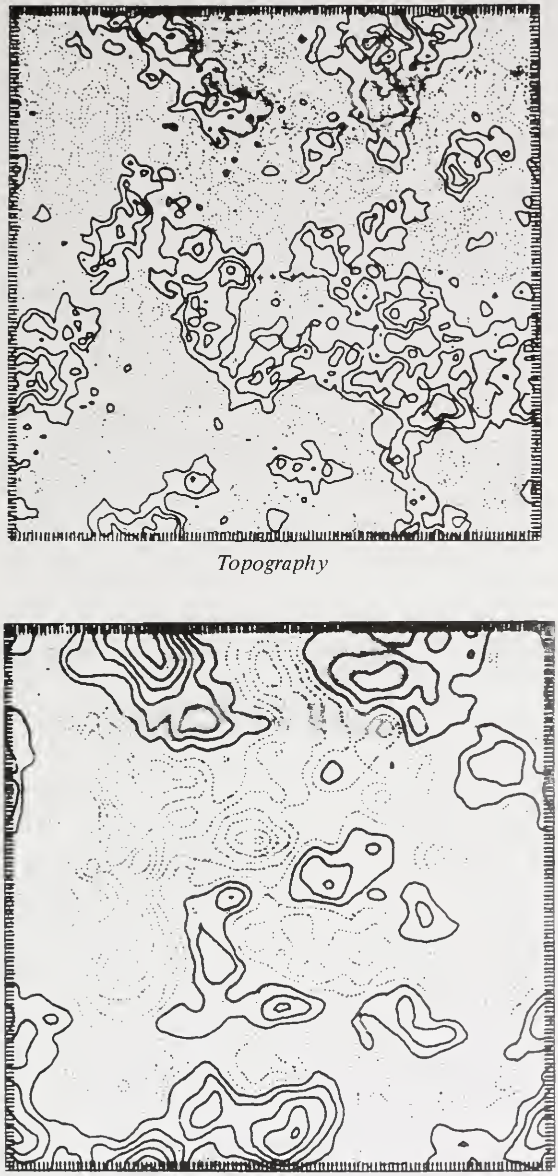


Figure 8. Flow patterns at four different depths in a fast-ocean model. Layer one is nearest the surface, layer six is nearest the bottom. Notice the smaller scale of the deep eddies, which respond to the sea-floor topography. Here the domain is 1000 kilometers square. The motions at the shallower levels are what I have called thermocline eddies. (From W. B. Owens, 1975, A numerical study of mid-ocean mesoscale eddies, Ph.D. dissertation, Johns Hopkins University, Department of Earth and Planetary Sciences.)



Topography

Streamlines

Figure 9. The development of strong eddies over rough bottom topography, in a single-layer (no pycnocline) ocean model. The eddies spontaneously develop into flow along the height contours of the topography. (Courtesy of G. Holloway and M. Hendershott)

Remember, too, that the ocean behaves differently at different depths. The eddies in fast oceans are able to transmit energy from the shallow water to the deep; there, remote from the force of the wind, they can again recombine to drive a large-scale circulation. This action is particularly important to the fate of water masses in the depths that are known to travel horizontally across entire oceans.

A particular example of the mean flow produced by a random pattern of eddies is shown in Figure 9. Here, as time progresses, the flow pattern more and more resembles the contours of ocean depth. Again, this induction effect appears to be a necessary consequence of the ability of eddies to diffuse a patch of marked fluid.

Conclusion

I have suggested that an ocean with a flat bottom, driven by very gentle winds blowing across its surface, would respond in a predictable fashion, with the eddy and circulation components formally independent. But the actual winds are far too strong for this to be a complete picture. Instead, a chaotic state prevails in which the circulation and eddies may in turn feed upon one another. Whereas eddies in slow oceans behave predictably as waves, those in fast oceans interact violently with one another, and react to the sea-floor topography. An empirical understanding of, and a firm statistical theory for, these interactions are beginning to emerge. The behavior of eddies will one day be as well grounded as, say, the classical mechanics of a vibrating string or a gas composed of colliding molecules.

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Figures 2-7 from P. Rhines, "The dynamics of unsteady currents," in *The Sea,* vol. 6, *Marine Modeling,* edited by E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, to be published in 1976 by John Wiley & Sons, New York.

POLYGON-70:
A Soviet Oceanographic Experiment

by Nicholas Fofonoff

The word ПОЛИГОН implies a test range or proving ground. For Soviet oceanographers, the series of POLYGON experiments conducted during the past two decades represents a focused effort to obtain oceanographic data to test theoretical concepts of ocean circulation. The POLYGON is the proving ground for ideas. As observed by Academician L. M. Brekhovskikh and his colleagues (*Proc. R. S. E.*, vol. 72, p. 34, 1972):

> . . . a collection of observations cannot replace a purposefully planned experiment. And as it has been figuratively put down by H. Sverdrup, at its early stage of development the situation in physical oceanography has been such that observations were carried out by many while few pondered over them. A sort of crisis of the 1940's and 1950's led to a new situation when, as V. B. Stockmann said, too many scientists were engaged in theory and calculations and only very few conducted purposeful measurements in the open ocean.

These scientists also point out that recent developments in theoretical oceanography, meteorology, and related sciences, combined with advances in technology, have converted descriptive physical oceanography into a physical science of the ocean. A similar realization of the gap between theory and experiment among Western oceanographers was expressed, for example, by H. Stommel in 1954 in a privately circulated note whimsically titled "Why do our ideas about ocean circulation have such a peculiarly dream-like quality?" in which he pleaded for oceanographic experiments designed specifically to test theoretical ideas.

POLYGON Experiments

Soviet oceanographers credit V. B. Stockmann with developing the concept of methodological research that evolved into the present series of POLYGON experiments. In 1935 Stockmann and I. I. Ivanovsky studied the structure of turbulence in the Caspian Sea. Using rudimentary equipment, they made a series of measurements over a three-week period from two anchored ships and found that current fluctuations were not closely linked to local winds and persisted even during periods of no winds. Their measurements enabled them to estimate momentum transfer by evaluating the correlations between current components—the Reynolds stresses extensively studied in turbulent flows.

At Stockmann's initiative, a long-range plan was developed during the postwar years to examine the structure of ocean currents and the relationship between the currents and the density field. It was not until 1956 that an experiment of comparable scope was carried out. A POLYGON in the Black Sea was instrumented with a moored buoy (42° 50'N, 40° 25'W) carrying current meters at 20 and 100 meters depth. Currents were recorded at 20-minute intervals for 18 days. During the same period, temperature and salinity were measured from two ships. The data from this experiment permitted a more detailed look at current fluctuations over time scales of a few hours to a few days. From the results of this work, R. V. Ozmidov concluded that the current fluctuations had characteristics of locally isotropic turbulence in that no preferred direction could be found.

The 1956 experiment is noteworthy in that a number of young Soviet oceanographers were brought together in a cooperative venture. It is this group that evolved and extended the POLYGON concept and that forms the core of present-day POLYGON oceanographers in the U.S.S.R.

The first venture to carry out similar research in the deep ocean occurred in summer 1958. Three buoys were anchored in the northeastern Atlantic (53° 44'N, 17° 31'W) in a right triangle with separations of 70 and 90 nautical miles. Measurements with current meters were made at depths of 50, 100, 200, and 400 meters recording at 30-minute intervals for about 14 days. Hydrographic stations were taken periodically at each location to determine the temperature, salinity, and density fields. This experiment revealed major

spatial variations of the currents over the short distances between the moorings, thus casting doubt on the ability to predict motion and density fields from a few point observations and indicating the need for a statistical approach.

In the decade that followed, new techniques of current measurement were developed in the U.S. and U.S.S.R. In 1965 the Woods Hole Oceanographic Institution Buoy Group (more formally called the Moored Array Project) established the 10-year time-series station (Site D, 39° 20'N, 70°W) at which many of the techniques and equipment for successful long-term deep-sea moorings were developed and tested.

The next POLYGON experiment was deployed in 1967 in the Arabian Sea by the Institute of Oceanology. This program called for 7 moorings instrumented at 11 depths from 25 to 1200 meters, with additional short-term moorings to measure to 4000 meters depth and to sample high frequencies (sampling at 5-minute intervals). A hydrographic survey was made in a 5-degree square enclosing the L-shaped moored array. The experiment lasted two months in order to examine spatial-scale fluctuations of 20 to 150 kilometers and time scales ranging from a few minutes to two weeks and more. A site with flat bottom topography was selected to minimize complications of flow interaction with the bottom. Program objectives included the following:

–To define the statistical characteristics of the currents, in particular their temporal and spatial spectra.

–To estimate how the magnitudes of terms in the equations of motion are affected by the area chosen for averaging.

–To test the "frozen turbulence" hypothesis (an assumption made to estimate spatial dimensions from a one-point time-series measurement).

–To determine location of energy sources in the frequency spectrum and to find direction of energy flow at the largest scale.

–To test the balance between pressure gradients and Coriolis forces (geostrophy). How well is the geostrophic balance satisfied as a function of scale or averaging? What are the adjustment time constants?

–To investigate properties of the vertical and horizontal structure of the velocity and other hydrological fields.

The Arabian Sea experiment represented considerable progress in the evolution of the POLYGON concept. Except for duration and level of effort, it had all the major components of present-day experiments. The results indicated that a period of two months was inadequate to resolve the full-time variability of the currents and that larger and longer POLYGONs would be necessary to encompass the full range of ocean variability. Such programs would call for further development of resources and organization. Plans for a long-term open-ocean experiment were already being formulated at the time of the Arabian Sea POLYGON. Also, initial discussions with U.S. oceanographers in 1969 led to consideration of possibilities for future joint efforts. These discussions continued through the early 1970s and established the foundations for POLYMODE, a major joint experiment scheduled for 1977-78, continuing at least one year and combining the oceanographic resources of both countries.

POLYGON-70

Several oceanographic laboratories of the Soviet Academy of Sciences, under the scientific leadership of L. M. Brekhovskikh of the Acoustics Institute and V. B. Kort of the P. P. Shirshov Institute of Oceanology in Moscow, joined forces to deploy POLYGON-70 in the Cape Verde Basin of the tropical northeastern Atlantic (16° 30'N, 33° 30'W) from February to September 1970.

The basic design of POLYGON-70 grew from objectives and considerations similar to those of earlier experiments, but the range and resolution of spatial scales studied were increased over those of the Arabian Sea POLYGON. A total of 17 surface-float moorings were set within a 2-degree

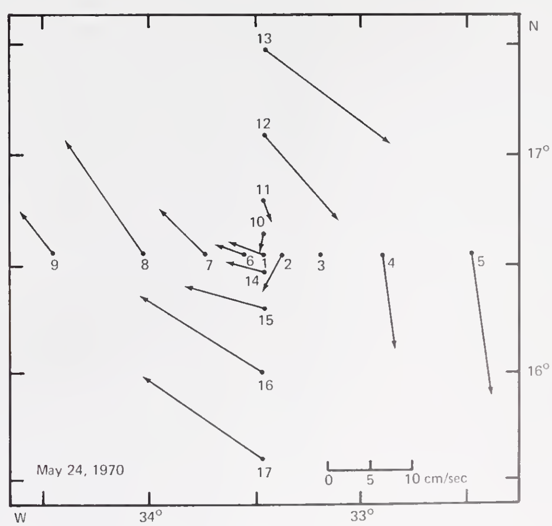

Figure 1. Three-day averages of current at 300 meters from POLYGON-70. Current vectors are shown at each of the 17 mooring locations. (Adapted from L. M. Brekhovskikh et al., 1971, Deep-Sea Res. *18:1189-1206, and L. M. Brekhovskikh et al., 1972,* Proc. R.S.E. (B) *72:351-56.)*

Photographs taken aboard the Soviet research vessel Akademik Kurchatov *in the Cape Verde Basin (off West Africa) in 1970 during the POLYGON experiment. (Photos by Charles Ross of Bedford Institute, Halifax, Nova Scotia. Text by Robert Heinmiller, POLYMODE Executive Manager, MIT.)*

Launching of the Soviet CTD (conductivity/temperature/depth) profiler "AИCT" ("Stork"). The instrument measured conductivity and temperature as a function of depth down to 200 meters, with the data transmitted up the conducting wire to a recording and processing unit aboard the ship.

A cylindrical surface mooring float on the foredeck after recovery. The float was made of low-density foam, with a central pipe for rigidity. The mast, with a sheet-metal radar reflector at the top, had broken off while the mooring was on station. It swung alongside the float, held by a wire-rope lift line, and gradually cut the gouge visible in the side of the float.

Anchors used on the POLYGON moorings. Made of cast iron, they were strung together in groups of three with heavy chain, for a total weight of about 700 kilograms. A swivel was inserted at the point where the anchors were attached to the mooring line.

Racks of Nansen bottles (for water sampling) in the passageway on the starboard side of the Kurchatov. *Additional stocks of bottles were carried in the hold for the seven-month trip.*

square in the form of a cross with north-south and east-west arms as shown in Figure 1. K. V. Konaev of the Acoustics Institute suggested the design based on antenna theory, to measure the selected band of wavelengths or spatial scales. This twofold increase in scale and threefold increase in duration represented a major expansion of the level of effort. Furthermore, the Arabian Sea experiment involved one ship (R/V *Vitiaz*), whereas POLYGON-70 required six ships—three to maintain the buoy array and three more to carry out the entire experiment.

R/V *Dimitri Mendeleev* (command ship of POLYGON-70) and R/V *Akademik Kurchatov* of the Institute of Oceanology maintained seven mooring positions each. The remaining three were tended by R/V *Andrei Vilkitsky* of the Navy Hydrographic Service. The moorings were replaced at 25-day intervals throughout the experiment—an operation requiring 7-10 days to complete. Visual inspections of each mooring were made about every 3 days, and any that drifted from their grid locations were repositioned. As a result, 90 percent of the moorings were recovered. However, such close inspection and maintenance consumed a large amount of ship time that could have been devoted to other research, and hydrographic coverage was therefore not as intensive as that in the U.S. MODE-1 (Mid-Ocean Dynamics Experiment, 1973).

Six hydrographic surveys were made approximately once a month during the experiment. Of these, two were large-scale surveys in a 2-by-2-degree square in August and a 3-by-3-degree square in September. Three other surveys examined the central region containing the moored array. In addition, north-south sections were occupied to investigate the surrounding ocean structure. In all, about 500 hydrographic stations were completed.

The program was supplemented by a variety of other measurements. R/V *Akademik Vernadsky* of the Marine Hydrophysical Institute of the Ukranian Academy of Sciences conducted microstructure studies using continuously profiling instruments. The two research ships of the Acoustics Institute, R/V *Sergei Vavilov* and R/V *Peter Lebedev*, carried out special acoustic experiments in addition to the hydrographic observations. Separate programs to study meteorology, air-sea interaction, geophysics, geochemistry, and biology were included in the overall project.

The major result of POLYGON-70 was the documentation of an energetic anticyclonic (clockwise) eddy that dominated the current field over the major portion of the experiment, as indicated by the current vectors in Figure 1. The eddy was elliptical, oriented NW-SE, with a length of 400 kilometers and a width of 200 kilometers. It drifted slowly westward at speeds of 4-6 centimeters per second and displayed orbital speeds ranging from 10 centimeters per second at 1500 meters depth, to 20-25 centimeters per second at 200-500 meters. The hydrographic surveys showed a density structure consistent with the currents but yielded lower speeds than the direct current measurements.

Preliminary results of POLYGON-70 were made available in 1972 to U.S. oceanographers for planning MODE-1 (see page 45). U.S.S.R. oceanographers K. Chekotillo, L. Fomin, and M. Koshliakov participated in a number of planning sessions in 1972 and were observers (together with Y. Grachev) during the experiment itself. Their experience was useful because it encouraged use of a mapping array and a more intensive density program in attempting a more detailed evaluation of the geostrophic balance than had been tried in POLYGON-70.

Analyses of both POLYGON-70 and MODE-1 data are still underway. Preliminary findings are being communicated among the scientists through meetings, newsletters, and formal publications. Since MODE-1, the pace of international meetings has escalated in preparation for POLYMODE. Scientists from both countries have pooled their knowledge and resources for a determined attack on the description and understanding of the eddy structure in the North Atlantic. POLYMODE represents the next major step in increasing our knowledge of eddies and their role in ocean circulation.

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The Mid-Ocean Dynamics Experiment

by Carl Wunsch

The Mid-Ocean Dynamics Experiment (MODE-1) was a large, intensive, and logistically complicated program conducted by physical oceanographers in the North Atlantic in mid-1973. From the participants' point of view, it marked an important step in changing fundamental ideas about the physics of the ocean. But, almost as important, it altered the way oceanographers go about their business.

MODE-1 was an exercise in the organizational aspects of oceanography almost as much as it was a scientific experiment, and its organization has tended to become a model for many other large oceanographic projects. For several years, beginning in 1970, MODE-1 absorbed the energies and talents of a substantial number of physical oceanographers from the United States and the United Kingdom and also consumed a significant fraction of U.S. and U.K. ship and equipment resources. Some scientists not involved in the experiment have occasionally claimed that this enormous focusing of effort was not entirely salutary—and not always when the individuals concerned were competing for the same resources.

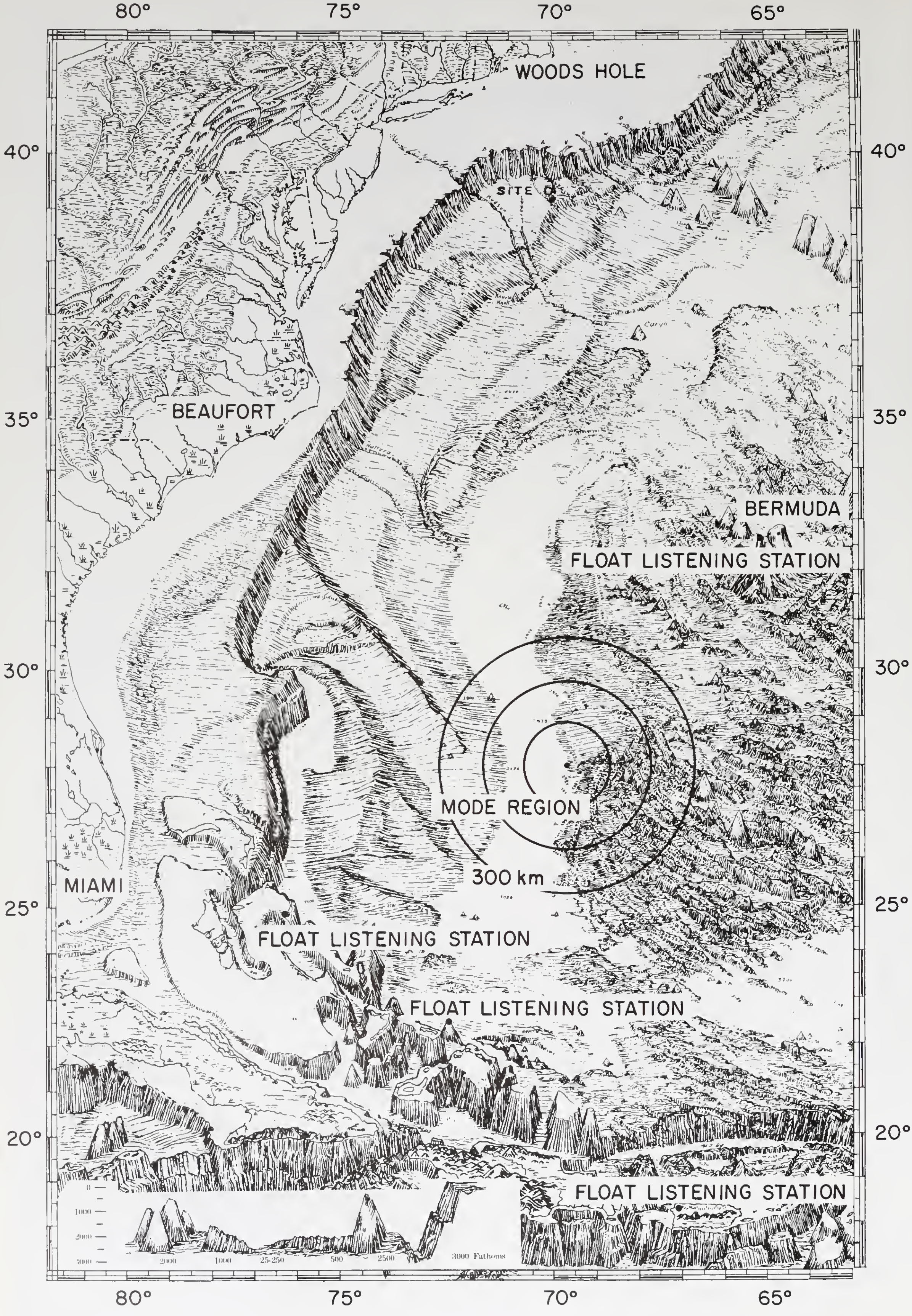
Origins of the Program

As with many scientific ideas, the roots of MODE-1 cannot be traced precisely. Most participants would undoubtedly cite as the key progenitor the measurements made by J. Swallow and J. Crease during the *Aries* expedition of 1959-60 (see page 20). That work can, in turn, be traced to a suggestion published by H. Stommel in 1955, and even before that to the general ideas of the time. The *Aries* measurements are indeed an obvious predecessor of MODE-1 because they suggested that something fundamental might be wrong with ideas about how the circulation of the ocean worked.

Theoretical models of ocean dynamics extant in the 1950s postulated a direct coupling between the ocean and the forces acting on it (large-scale winds and solar heating). The hypothesized response was thus a smooth, sluggish mean flow. An analogy can be made by supposing that in the atmosphere there were only *climate*—hot tropics, cold poles, large regions of desert, and so on, with a slow drift of air between them. There would be no *weather* in the commonly accepted sense, for example, no northeasters, hurricanes, and squalls.

Of course, no one would leave out the weather in trying to realistically model the atmosphere, for by observation alone it is obviously a dominant feature. But in the ocean, only observations of climate were available, recorded in the atlases of the temperature and salinity and mean currents compiled so painstakingly over the years, beginning with the *Challenger* expedition (1872-76) and before.

Thus when new technology made available direct measurements of deep-ocean currents, one could see for the first time that there might be something analogous to weather in the ocean. If this were indeed the case, then by analogy both to meteorology and to laboratory studies of turbulence, most details of theories of how the ocean worked might then be incorrect. For example, meteorologists believed for many years that "weather" simply represented the means by which the overall climatic circulation dissipated energy. That is, energy was put into the system by the overall heating at the equator and cooling at the poles, and storms in general represented a mechanism by which the system generated smaller scales on the road to ultimate frictional dissipation. But beginning in the early 1900s and culminating with observations made possible in the 1950s, meteorologists found that the system was much more complicated, and elegant, than they had thought. In many parts of the atmosphere, the smaller-scale storms (often called eddies) were feeding energy *into* the climatic circulation—driving it, instead of the reverse. Thus the notion of a climatic circulation that could be considered in any way independent of the storms or eddies also present was quite wrong.


80°
75°
70°
65°
WOODS HOLE
40°
SITE D
BEAUFORT
35°
BERMUDA
FLOAT LISTENING STATION
30°
MODE REGION
300 km
MIAMI
25°
FLOAT LISTENING STATION
FLOAT LISTENING STATION
20°
FLOAT LISTENING STATION
0
1000
2000
3000
2000
1000
25-250
500
2500
3000 Fathoms

The possibility that this might also be the case in the ocean was obvious to most of those who thought about it. The importance of the question of how the general circulation of the ocean is controlled should not be underestimated. Apart from the purely intellectual challenge of knowing how this remarkably complex and interesting enormous fluid dynamical machine works, there is the practical aspect of understanding the effects of ocean currents on global climate, fisheries, and pollutants.

Between 1960 and 1970, almost nothing specific was done about the problem. For, while the *Aries* measurements were the result of a new technology making available new measurements and changing ideas, there seemed no way to follow up all the disturbing possibilities suggested. The technology was not in fact adequate to deal with the problem. For as Swallow has pointed out many times, the vessel available could not keep up with the floats, and it appeared they would have to be followed for many months or more for one to learn much. Altogether the instruments seemed mismatched to the magnitude of the problem they suggested.

During the 1960s oceanographers had occasional discussions about whether anything might be done, but the consensus was always that appropriate instrumentation was not available to operate in the deep sea for the very long periods of time that seemed necessary. However, technical developments were underway that kept provoking these intermittent discussions: for example, neutrally buoyant floats that could be tracked from land stations (rather than from ships) at 1000-kilometer ranges for up to a year; deep-sea moored buoys capable of staying in place for several months at a time; deep-sea pressure instruments that could function almost like barometers; and instruments capable of measuring the vertical profile of horizontal currents in a few hours (see page 59).

Planning Stage

In early 1970, scientists involved in the new instrumentation began to meet informally; a consensus emerged that, finally, something could and should be done. The physical oceanographic community as a whole, including theorists, was brought into communication, and serious planning for the experiment began.

Location and topography of the MODE-1 area are indicated on a portion of the Heezen and Tharp physiographic diagram of the North Atlantic. (Portion of the physiographic diagram of the North Atlantic Ocean, published by the Geological Society of America, Boulder, Colorado. Copyright 1968, Bruce C. Heezen and Marie Tharp. Reproduced with permission.)

Because of the developmental nature of many of the available instruments, as well as general ignorance about the phenomenon to be studied, the planning of MODE-1 went through several stages. The ignorance factor was in many ways the biggest problem. If one were looking for ocean weather for the first time, where should one go, what should one measure and for how long? How big were the "storms"? For this reason, MODE-1 was originally called Pre-MODE and envisioned as the pilot experiment for a proper mid-ocean dynamics experiment to come later (the name was later changed when the organizers were told that governmental funding would not be available for "pre-anything"—it had to be a "real" experiment). The new and not-as-yet thoroughly tested nature of much of the instrumentation led the initial planning to be based upon the cautious principle of children playing in a sandbox: nominally playing together, but each in fact building his own sandcastle. MODE-1 was to consist of individual experiments conducted in the same area; but because of fears of instrumentation failures, no one element was to become so crucial that its failure or loss would jeopardize the others. As it turned out, this quasi-independence was vital.

In retrospect, the planning of MODE-1 was comparatively simple. The experiment had a high degree of inevitability about it—a consensus really did exist that a program of this sort was necessary and feasible at the time. The planning was made fairly simple for several reasons: the "mid-ocean" location (a 600-kilometer-wide area between Bermuda and Florida) was dictated largely by the need for proximity to U.S. East Coast ports, and the need to be within the tracking range of the large neutrally buoyant floats; the duration was constrained by the endurance of the instrumentation; and, most important, almost nothing was known about open-ocean variability. For this last reason, no matter what the detailed design of the experiment, whether or not mistakes were made, success was virtually assured. Almost any new measurements were bound to be enormously enlightening.

Very early on, the scientists responsible for bringing together disparate investigators, instruments, institutions, and ships to collaborate in one small area at a single time, found the need for an administrative structure. Problems to be discussed ranged from the question of whether there was any relevant theory of the circulation of

the ocean, to such specific issues as making sure that acoustic signals from different investigators did not interfere with each other, and that the six ships and two aircraft involved could communicate with each other and with the scientists ashore. Consequently an elaborate committee structure evolved, as shown in a simplified schematic in Figure 1, and nearly three years of meetings and discussions ensued.

The sandbox principle was generally accepted, but of course everyone wanted to make the best use of the simultaneous presence of diverse instruments: to achieve redundancy and intercomparisons; to take advantage of anything the theorists could agree on; and, generally, to make the best possible experiment. Of necessity, steering groups emerged, as did a MODE-1 bureacracy as an inevitable adjunct. Most of the MODE-1 scientists were unfamiliar with this kind of organization in their professional lives, and many of them found the whole business of dealing with a centralized, highly planned experiment, increasingly traumatic. Traditionally, sea-going oceanographers have been an individualistic lot, with a strong tendency to be scientific-loners. A not untypical working life meant going to sea for a few weeks each year, with the scientist in complete charge of the use of the ship, and while at sea responsible in his science to no one but himself. Upon completion of the work at sea, several months would be devoted to working up the data for publication; then plans made for the next set of observations at sea, and the whole process would begin again. So, despite the fact that working at sea required a crew and scientific watchstanders, the scientist in charge was more or less captain of his own fate and able to do effective "small science." There can be few more tangible, and deeply satisfying, experimental scientific experiences than having nearly complete control of the movements of a large vessel and perhaps 50 supporting crew and scientists.

With the advent of MODE-1 many oceanographers saw all this changing. Almost everything had to be negotiated with a scientific bureaucracy, endless meetings and negotiations had to be endured, and even the traditional autonomy of the chief scientist while at sea seemed to be disappearing—he was now answerable to a communications center in Bermuda and to a willful executive committee. In general, the specter of high-energy physics emerged—it looked as though the resulting scientific papers would need 25 co-authors. Big science really seemed to have arrived in oceanography, and what many people saw of it, they disliked. Much of the experimental nature of

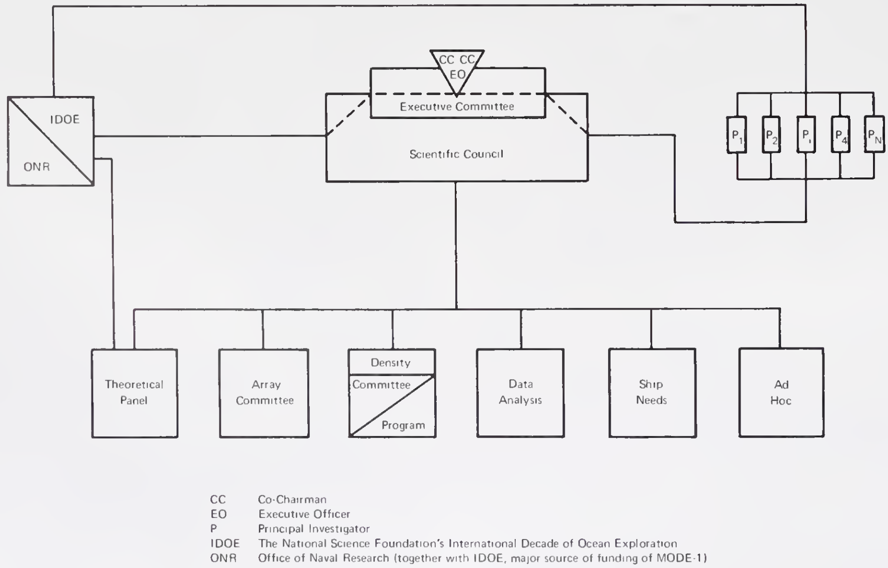


Figure 1. MODE-1 scientific management diagram. (From "MODE-1: The Program and the Plan," Appendix 2. MODE-1 Executive Office, 54-1417, MIT, Cambridge, Massachusetts.)

Cameraman films the launching of a current meter from the fantail of R/V Chain *for a documentary on MODE-1 entitled* The Turbulent Ocean. *(Harold Armstrong)*

MODE-1 thus consisted of finding out if a lot of individualistic oceanographers could in fact bring themselves to work together.

Another semisociological problem lay in the relation between theorists and sea-going scientists. Of course, there is and always has been an intimate and continuing interaction between theory and experiment in physical oceanography, but this has tended to exist between individuals, and then mostly through the reading of each other's papers. In MODE-1, theorists and experimentalists were trying to work directly together in planning a joint experiment on a very large scale. Theory was meant to advance hand-in-glove with new observations in a way that had not happened before.

At Sea

At the end of three years of planning, argument, crisis, and much sweat, the experiment went to sea east of Florida in early March 1973. Its final complement involved an international group of more than 50 oceanographers representing 15 institutions, several hundred scientific participants, 6 ships, and 2 aircraft. A list of all institutions and principal investigators and most of their projects is shown in Table 1. The field experiment was very complex. Moorings and floats were being set, the aircraft were dropping profilers, the ships were all measuring the density field, and continual changes in strategy and tactics were being made as data came in and problems occurred. To tie together the disparate elements and to provide communications, a "hot line" was set up linking the ships and aircraft by radio to a "hot-line center" in Bermuda and by leased cable to five U.S. institutions on the mainland. Innumerable conference calls ensued in which scientists on several ships talked with the center chief scientist on Bermuda and, simultaneously, with members of the executive committee and others at the various U.S. institutions.

If having control of a single ship can provide a sense of power, the notion of controlling a fleet is an even more tempting prospect. Not surprisingly, a number of would-be admirals emerged. But despite an occasional tremendous clash of wills, common sense usually prevailed. Participants generally followed the principle that the man-on-the-spot, the chief scientist on the ship at sea, is in the best position to judge his problems and possibilities. And most of the scientists at sea seemed happy to have the advice of those ashore on how best to use the ships for the overall good.

At the end of the intensive four-month field period, a vast amount of new data emerged and the long process of making sense of it began.

Table 1. **Projects, principal investigators and institutions in MODE-1**

Moored current meter arrays		
16 moorings with 4-8 current meters each	N. Fofonoff, W. Schmitz, and F. Webster	Woods Hole Oceanographic Institution
5 moorings with 4 current meters each	J. Swallow	National Institute of Oceanography, England
8 moorings with 1 or 2 current meters each	J. Knauss and W. Sturges	University of Rhode Island
Bottom-mounted instruments		
2 IGPP capsules, 1-month lifetime; 1 IGPP capsule, 1-year lifetime (temperature, current, pressure bottom kilometer)	W. Munk, F. Snodgrass, and W. Brown	Institute of Geophysics and Planetary Physics, Univ. of Calif., San Diego
6 inverted echo-sounders	H. T. Rossby	Yale University
3 electric-field recorders and 3 bottom-mounted magnetometers	C. Cox, V. Vacquier, J. Filloux, and R. Parker	Scripps Institution of Oceanography
5 bottom-pressure recorders (fused silica bourdon type)	D. J. Baker, Jr.	Harvard University
Float tracking		
20 long-range SOFAR-type floats using MILS listening stations	A. Voorhis, D. C. Webb, and H. T. Rossby	Woods Hole Oceanographic Institution and Yale University
36 intermediate-range acoustic floats tracked by shipborne hydrophones	J. Swallow	National Institute of Oceanography, England
Hydrophone arrays for locating SOFAR floats	R. Walden and H. Bertaux	Woods Hole Oceanographic Institution
Density measurements		
Shipboard STD and CTD casts	D. Hansen	Atlantic Oceanographic and Meteorological Laboratory
	J. Crease	National Institute of Oceanography, England
	A. Leetmaa	Atlantic Oceanographic and Meteorological Laboratory
	R. Scarlet	Massachusetts Institute of Technology
Moored thermal array		
60 temperature-pressure recorders (on WHOI moorings)	C. Wunsch	Massachusetts Institute of Technology and Draper Laboratory
Towed instruments		
STD tows to map isopycnal surfaces	E. Katz and R. Nowak	Woods Hole Oceanographic Institution

Free-fall instruments		
Velocity profilers acoustically tracked by using bottom-mounted transponders	T. Pochapsky	Columbia University
Electric-field free-falling probe and bottom recorders	T. Sanford	Woods Hole Oceanographic Institution
Displacement-type current probe, airborne expendable (2000)	W. S. Richardson	Nova University
Numerical modeling and theoretical studies		
Synoptic maps for MODE-1	F. Bretherton	The Johns Hopkins University
Interactions between short internal gravity waves and larger-scale motions in the ocean	K. Hasselmann	University of Hamburg
MODE-1 array design as an inverse problem	M. Hendershott, R. Davis, and W. Munk	Scripps Institution of Oceanography
Theory and computer experiments on oceanic eddies and waves	P. Rhines	Woods Hole Oceanographic Institution
Analytic and numerical studies of mesoscale motions	A. R. Robinson	Harvard University
A theoretical-numerical study of geostrophic eddy motions in the oceans	P. Welander	University of Gothenburg
Administrative		
Funds for travel, executive officer, meetings, etc.	H. Stommel and D. Moore (on leave from Nova University)	Massachusetts Institute of Technology
	Additional associated projects	
5 Filloux-type bottom-mounted tide gauges and 1 Hewlett Packard pressure gauge	H. Mofjeld	Atlantic Oceanographic and Meteorological Laboratory
Monitoring earth's magnetic field at island stations	J. Larsen	University of Hawaii, Hawaii Institute of Geophysics
Bottom-mounted vertical electric-field measurements	R. Harvey	University of Hawaii, Hawaii Institute of Geophysics
Bottom-mounted magnetometers	R. Von Herzen	Woods Hole Oceanographic Institution

Source: *"MODE-1: The Program and the Plan," Appendix 1. MODE-1 Executive Office, 54-1417, MIT, Cambridge, Massachusetts.*

Many of the results are discussed in other articles in this issue.

The Outcome

As already mentioned, MODE-1 was in many ways failure-proof. Barring some catastrophe, there was no way that the experiment could have failed to increase, by orders of magnitude, our knowledge of open-ocean variability. In its overall goals MODE-1 was thus an overwhelming success: it was confirmed that an open-ocean eddy field ("weather") existed; individual eddies, at least in that area, had lifetimes exceeding many months; and the simplest notions about eddy behavior were confirmed. The fact that the eddies were found to be exceedingly energetic strengthened the hypothesis that they probably have some profound effects on the mean ocean circulation. As the MODE-1 data are studied in the years ahead, more surprises about the ocean are certain to emerge.

To a considerable extent, there has been a revolution of ideas. The notion of a slow, sluggish general ocean circulation driven directly by the climatological average winds and heating is gone forever. Most older models of global circulation have been reduced to mathematical curiosities—interesting and useful as they were in their day, no one any longer believes that the ocean works like that. The idea that eddies in some way control the movement of the water is rapidly being assimilated into studies of oceanic chemistry, biology, and meteorology in a way not even thought of a few years ago. Even at this comparatively early stage, it does seem fair to say that MODE-1 was worth all the travail of getting it done.

Where do we go from here?

The Next Step

As noted earlier, MODE-1 was originally called Pre-MODE, the predecessor to a proper mid-ocean dynamics experiment, and it was not envisioned as in any sense completing the study of the role of eddies in ocean circulation. Even before the first results of MODE-1 had been completely assimilated, planning began for the next step. MODE-1 made very clear the magnitude of the problem now at hand. To observe anything like the full-time evolution of an eddy in the MODE-1 area means many months of intense observations in that region. But is the MODE-1 area in any way typical of the rest of the oceans? If one understood the MODE-1 area completely—and we are a long way from that—would that mean one understood the physics of eddies in all other parts of the ocean? It seems unlikely. Understanding the ultimate question of MODE-1—the role that eddies play in the general circulation of the ocean—will require many years of measurement in many different parts of the oceans. The magnitude of the task is great, so great in fact that it seems too much for the resources of any one or two countries. The next phase seems to demand the resources of much of the entire international community of physical, and to some extent chemical, oceanographers. Recognizing this fact, the U.S., U.S.S.R., U.K., Canada, France, and West Germany are taking the next experimental and theoretical steps under the rubric POLYMODE (from the Soviet POLYGON and the U.S. MODE).

Paradoxically, the planning for POLYMODE is much more difficult than it was for MODE-1. In the face of nearly total ignorance prior to MODE-1, the outline of that experiment was almost inevitable. But now we know a great deal, and that knowledge implies many second steps that could be taken, any one of which would provide significant data on some aspect of the eddy problem, but each of which would tend to use up so many of the limited resources that it would preclude immediate progress in other, equally promising directions. Thus, considerable discussion and heated argument have gone on since the end of MODE-1 concerning the choice among many appealing options. To the outside oceanographic community it has sometimes seemed as though the POLYMODE oceanographers cannot agree on anything and do not, in fact, have a program. But the problem arises through legitimate and productive disagreement about an abundance of scientific possibilities.

Indeed, out of the wrangling there has emerged considerable agreement about POLYMODE, and the experiments planned for the next three years are quite definite. It is now generally agreed (there are still some dissenters) that the most pressing problem is finding out whether eddies are basically of one type, or whether there is an eddy "zoo." If one looks in a different part of the ocean, does one see motions like those of MODE-1, or something completely different? Until that question is answered, it will be difficult for theorists to come up with models of how the ocean works.

There are already hints. Gulf Stream rings (see pages 65 and 69) are a form of eddy. They look quite unlike the MODE-1 eddy, and there is some evidence that their physics may be at least somewhat different. We already know that as one moves out of the MODE-1 area, the energy of the eddy field changes markedly. But what does this change mean?

To pursue our meteorological analogy a little further, MODE-1 may be thought of as a weather-observing program that managed to observe a three-day New England northeaster for a little over two days, and that this was the only storm ever really seen. One would then have a long string of questions: Do northeasters occur in New England all the time? If not, how often? What happens in between? Are these storms typical of weather in all parts of the world?

During MODE-1 there was an oceanic "storm." Are there analogues to hurricanes—with all their climatic implications—in the MODE-1 area and elsewhere? How long would we have to measure to see one? Or are Gulf Stream rings an analogue to hurricanes? We do not know the answers to any of these questions.

Thus the POLYMODE program is taking the first steps toward global answers. Because of the long time scales in the ocean, the difficulties of measurement, and the logistics, these answers will be many years in coming. If the true measure of the success of an experiment is whether it generates many more questions than it answers, MODE-1 was an overwhelming scientific success.

The sociological, organizational aspect of MODE-1 may also be judged a success—it got the job done. On the other hand, working within a highly organized program did not appeal to all of the participants, many of whom flinch at the prospect of POLYMODE, which, because of its wider international participation, tends to be an even greater tax on time and patience for bureaucratic purposes. Many of the MODE-1 scientists have gone back to their old ways, back to "small science." Fortunately, oceanography still has many areas where "small science" continues to be the best way to do things. And there is no denying that it is much more fun.

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The MODE-1 central mooring is prepared for launch to serve as a navigation reference and to gather weather data. One night during the experiment, the large buoy was "recovered" by an unknown ship and was never seen again. (Susan Tarbell)

Instrumentation for MODE-1

Recovery of a MODE-1 mooring by R/V Chain. *Each of the units shown here is a glass sphere in a protective plastic case ("hard hat"). Each unit gives about 25 kilograms of buoyancy. (Susan Tarbell)*

by W. John Gould

Almost all of our knowledge of mid-ocean eddies has been acquired during the present decade. This may seem surprising, but the reason for the recent upsurge can be directly related to our ability to make certain kinds of measurements in the deep ocean.

Eddies are dynamic features, and although they may be detected and identified by detailed temperature maps, a full understanding requires that dynamic measurements be made. We must be able to determine the velocity of water in the deep ocean for periods long enough, and over an area big enough to be able to "see" an eddy, to measure its energy and velocity structure. The ability to make such measurements has evolved over the past fifteen to twenty years, during what has seemed a long, slow, and often frustrating process. Our present skills can be put into perspective by considering the development of two important instruments in deep-sea measurement—the neutrally buoyant float and the current meter.

In the mid-1950s our knowledge of deep-ocean currents, from direct measurements, was sparse. K. F. Bowden in 1954 could summarize all the previous measurements in a single paper in the journal *Deep-Sea Research,* and the total duration of all those records was counted in hours rather than days. Bowden's paper awakened the oceanographic community to the lack of direct information about ocean currents. In an attempt to alleviate the problem, H. Stommel, in a letter to the same journal, suggested the development of a new technique to measure ocean currents. During World War II M. Ewing found that there was an optimal depth for the transmission of sound horizontally over long distances underwater. Stommel therefore suggested that this SOFAR (SOund Fixing And Ranging) channel could be used to fix the positions of freely drifting neutrally buoyant floats by receiving their signals at listening stations on islands in the Atlantic.

The first attempts to make neutrally buoyant floats for tracking deep currents were not so ambitious as Stommel's SOFAR float idea. J. Swallow at the British National Institute of Oceanography (now Institute of Oceanographic Sciences) set about developing a neutrally buoyant float that could be followed from an attendant ship.

The body of the float, which had to withstand the pressure at which it was to work, be sufficiently buoyant to carry all the necessary batteries and electronics, and be less compressible than seawater, was made of a pair of 3-meter-long aluminum scaffolding tubes—one to provide buoyancy, the other to hold the batteries and electronics. The floats were designed to be used to a depth of 4500 meters and for a lifetime of about 3 days, with acoustic signals transmitted every few seconds. In 1955 Swallow reported two float tracks of 2 and 3 days at 900 and 400 meters from an area west of Portugal. The measured speeds were low (5.7 and 2.4 centimeters per second) and thus were not inconsistent with the previously held ideas about the slow, steady movement of deep-ocean currents (see page 28).

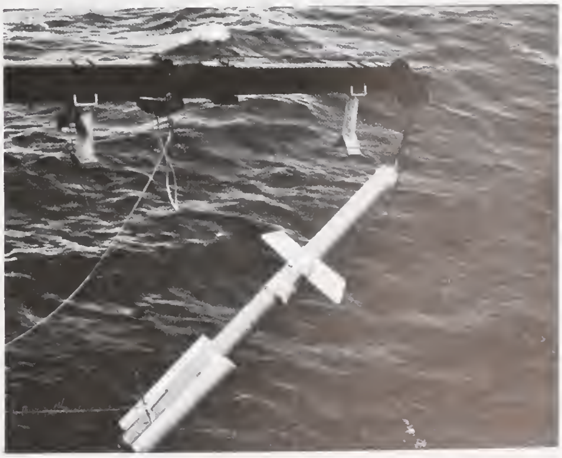
The first major experiment with neutrally buoyant floats was the attempt by Swallow and J. Crease, working from the *Aries*, to make long-term measurements of deep currents southwest of Bermuda. The measurements were made between June 1959 and August 1960 and revealed that deep currents in that part of the open ocean had energies much higher than originally thought and that much of the energy was contained in features with apparent wavelengths of typically 100-200 kilometers. This work, in addition to providing the first look at deep-ocean variability, showed that if the deep ocean in general was as variable as the measurements suggested, then the difficulties involved in the prolonged use of the existing tracking technique for neutrally buoyant floats (chasing each one by ship) would be great and that a larger-scale experiment would be prohibitively expensive in ship time (see page 20).

The current speeds recorded during Swallow's early measurements stimulated a parallel line of attack. It was considered that such currents might be fast enough to be measured by recording instruments (current meters) attached to moored buoys in the deep ocean. Toward this end, W. Richardson, then at the Woods Hole Oceanographic Institution, began to develop the appropriate instruments and mooring techniques. The current meters used a vane to read the direction of current flow relative to an internal magnetic compass and a rotor made from "back-to-back" half cylinders to sense current speed.

A test mooring was set near Bermuda in December 1960 that consisted of a toroidal surface float connected by polypropylene line to an anchor on the sea bed, with the recording current meters inserted between the lengths of rope. It was successfully recovered in late February 1961, having survived winter conditions for 79 days, and the design was quickly adopted. In early May 1961 four such moorings were set on the continental slope and shelf south of Cape Cod, but by the end of the month only one was completely recovered.

At this point and in spite of the losses, the most ambitious part of the project was begun: the maintenance of a line of 13 moorings with 62 current meters between Cape Cod and Bermuda. Attempts to maintain this buoy line throughout the year that followed revealed that there were a multitude of hitherto unknown difficulties with both the mooring design and the instrumentation. Many moorings were lost, some totally; others were recovered adrift from their proper positions after mooring lines had parted.

The current meters, which recorded their data on 16mm film, posed problems that were attributable to the dynamic response of the instruments in the mooring line; oscillations and rotations that could not be adequately resolved by the instrument made many records either difficult or impossible to read. Although solutions were found for most of the problems as they arose, a decision was made in 1962 to abandon the "Bermuda line," and in 1963 there was a major change in emphasis. Efforts were directed toward engineering studies of the mooring and current meter problems. Among many other developments, these studies led to the use of subsurface moorings that were unaffected by weather at the sea surface and thus stood a better chance of surviving winter storms. Current meters were redesigned to record their data on magnetic tape instead of film, greatly simplifying the subsequent data analysis. As problems were



One of the instrumented SOFAR floats. At the bottom of the float are the two low-frequency sound projectors. Angled fins around the float body convert vertical motions relative to the water to rotations. (See SOFAR float tracks, pages 14 and 27.)

solved, the accumulated knowledge of deep-ocean currents increased, and by the late 1960s the deployment and recovery of moored current meters had become a relatively routine operation.

The first attempt to study mesoscale eddy features over a large area was the Soviet POLYGON experiment of 1970 (see page 40). It required a great deal of effort by the ships and people involved to maintain the large array of 17 moorings for the 8-month period, each buoy having to be replaced at 1-month intervals. However, the techniques used were well tried and thus did not involve a high risk of instrument failure.

MODE-1 Instrumentation and Design

From the outset the design philosophy of MODE-1 (Mid-Ocean Dynamics Experiment) differed from that of POLYGON in the types and complexity of instruments used. While some of the measuring techniques were well tried, others were entirely new. In many cases MODE-1 was a testing ground for new instruments.

The main objective of the program was to map both the velocity and the density field over the MODE-1 region, although additional experiments were incorporated to provide other indirect recordings of the influence of mesoscale eddies. Primary measurements included the mapping of currents from moored buoys, neutrally buoyant floats, and vertical profiles, and the measuring of densities from CTD (conductivity/temperature/depth) and STD (salinity/temperature/depth) profiles, XBT (expendable bathythermograph) profiles, and a towed CTD.

Moored Arrays

The mooring techniques used to map the horizontal velocity field were all directly related to those developed over the previous decade. The sixteen instrumented moorings all had subsurface buoyancy.

In the planning stages it was thought that a combination of subsurface and surface moorings could be used, with the surface buoys serving as platforms from which meteorological measurements could be made. It was found at a relatively late stage that the measured values of currents were dependent on the type of mooring used (the vertical motions of the surface float are transferred down the mooring line and can have a large effect on the current meters, particularly in the deep water where velocities are low).

The current meters used by Woods Hole Oceanographic Institution were of the then relatively new vector averaging type (VACMs). These had been developed at Woods Hole by R. Koehler and J. McCullough with a view to improving the performance of existing current meters in situations where there might be a large amount of high-frequency energy (such as on surface moorings). Even though all the MODE-1 moorings were subsurface, and not subject to such conditions, it was thought that the much simpler data processing made possible by VACM records would provide speedier dissemination of information among the MODE-1 scientists. With some 83 records to be processed, this was an important factor.

In fact the most sophisticated and new parts of the VACM gave little trouble. These were the internal computer, which calculated the east and north components of velocity from the speeds and directions measured by the rotor and vane, and all the associated logic circuitry. The main failing of the VACM in that experiment came from a totally unexpected quarter.

As the records were decoded it was found that the response of the rotors and vanes became progressively more sluggish as the experiment progressed. The problem was later traced to a buildup of carbonate compounds in the bearings. The stagnant water in the bearings had acted as an electrolytic cell driven by leakage currents through the sacrificial anode on the pressure case. Not all

The recovery of a vector averaging current meter (VACM) during MODE-1. (IOS)

the VACMs suffered from this problem and since other, older types of current meter were also used in the experiment the result was not disastrous.

Neutrally Buoyant Floats

The other main method of current measurement used in MODE-1 employed neutrally buoyant floats that were tracked via the SOFAR axis by a technique not too far removed from Stommel's original concept. The floats were tracked from land-based listening stations via low frequencies (267-273 hertz at a nominal 1-minute repetition rate and with a pulse length of 1.667 seconds). The floats could also be located by surface ships via a separate high-frequency (10 kilohertz) system, which included an acoustic command recovery capability to release external ballast and return the float to the surface.

The low-frequency shore-based tracking system obtained acoustic ranges to the floats from a maximum of four listening stations in Bermuda, Eleuthera, Puerto Rico, and Grand Turk Island. This was done by measuring the difference between the time of transmission at the float and that of the arrival at a pair of stations. The transmission signal was controlled by a temperature-stabilized quartz clock in each float having an accuracy of better than 1 part per million (approximately 1 second in 12 days). The float signals were distinguished from each other by having a possibility of 3 transmission frequencies and 7 repetition rates, thus giving 21 separate channels. Half of the twenty floats used in MODE-1 carried additional instrumentation to monitor vertical water movement, water pressure, and temperature. The vertical motions of the instrumented floats relative to the water were converted to a rotation by a set of angled fins around the circumference of the float, and the number of rotations, together with the temperature and pressure data, were recorded on a digital magnetic tape recorder every 256 seconds.

All the floats were ballasted to stabilize at 1500 meters, and all of those instrumented showed initial depths of 1525$\pm$24 meters. However, the records indicated that the floats sank by 15 meters during their first day after launch and that the sinking rate stabilized at 0.85 meter per day after about 2 weeks. This effect has been traced to the slow compression of the aluminium float bodies under the sustained high pressure. This sinking had no serious effect on the value of the data.

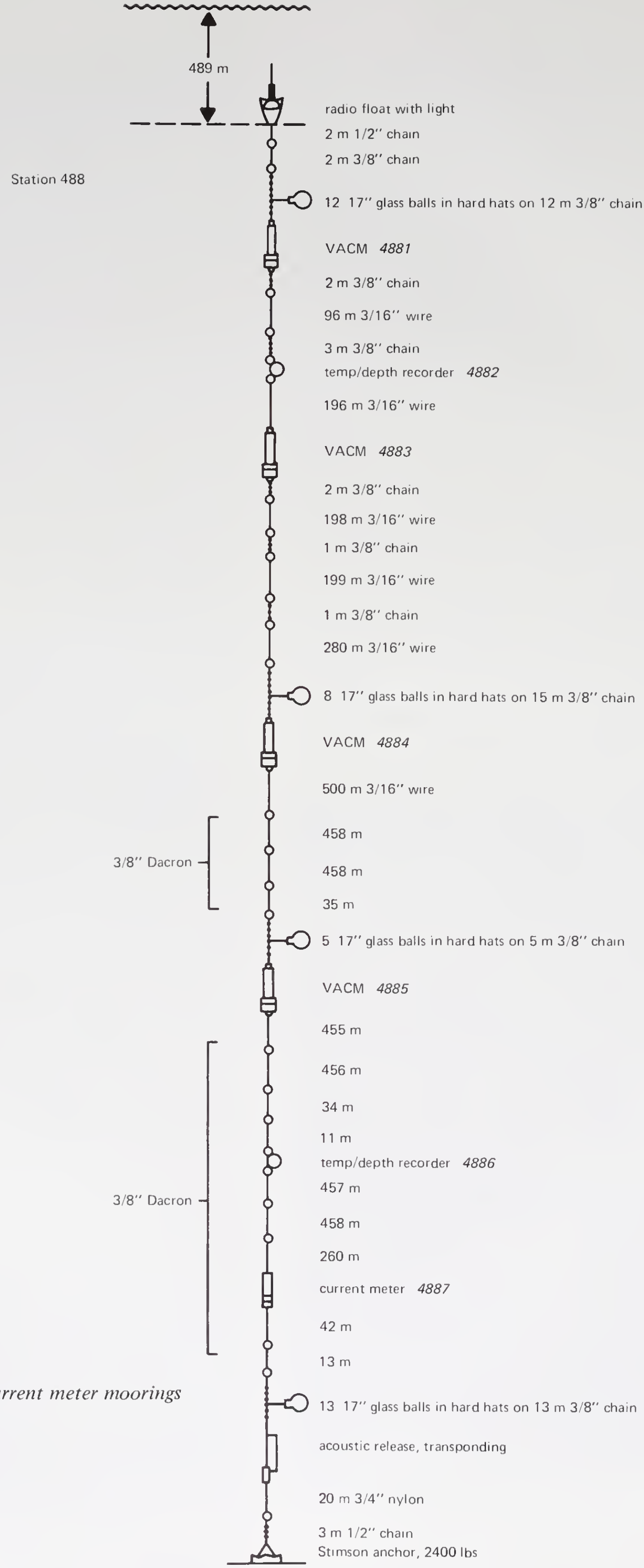
A rather more serious, though temporary, fault appeared early in the experiment. Several of the floats stopped transmitting their low-frequency signals after less than two weeks in the water. These floats were tracked and recovered via their high-frequency transmitters and were found to have a failure of the low-frequency sound projectors. Fortunately in almost all cases only one of the two projectors in each float had failed and then shorted the remaining good projector. Temporary repairs were made at sea and the floats relaunched; meanwhile a new projector seal was designed and was installed in all the floats as early as possible.

The shore-based positioning of the floats was found to have a random route mean square error of about 500 meters (about half the design specification). At the end of the main MODE-1 field experiment (July 1973) all the floats were recovered, their batteries were recharged, and they were relaunched for an indefinite drift (the repetition rate was cut by one-third to prolong battery life). Many of these floats were still being tracked late in 1975.

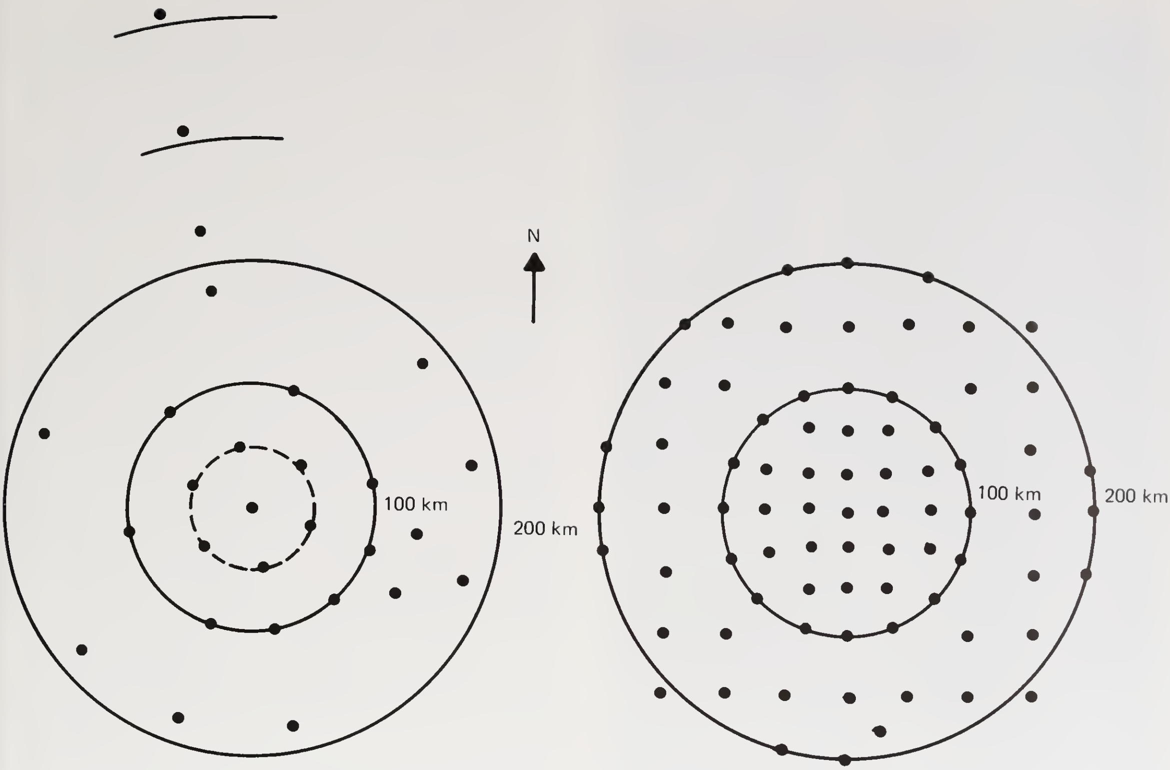
Swallow Floats

The SOFAR floats were restricted to use near the sound axis at 1500 meters, and thus no comparisons between Lagrangian (drifting) and Eulerian (moored) current measurements would have been possible at other depths. Lagrangian current measurements were made at scales smaller than the typical mooring separation of the main array. These were the sort of scales at which the ship-tracked neutrally buoyant floats developed by Swallow could be used. However, it was necessary to track about 4 or 5 floats simultaneously at each of the 4 standard current meter depths (500, 1500, 3000, and 4000 meters), and this would have been totally beyond the capacity of any system used by the National Institute of Oceanography (NIO) up to the time of MODE-1 planning. So a totally new system was designed.

The floats, rather than transmitting sound continuously, would act as transponders (transmitting only when they received an interrogation pulse from the ship). They would be recoverable so that they could be reused and would be able to be tracked even when the ship was engaged in other work such as making STD or CTD observations. The technique for fixing a group of floats would be to transmit a signal from an interrogator attached beneath the CTD probe. All the floats within listening range would reply, and from the time difference between the outgoing and return pulses the horizontal range to each float could be calculated. Thus from the ship position each float would be known to lie on the arc of a circle. Floats that could not, due to the ray paths, be detected from one level might be contacted by



One of the MODE-1 WHOI current meter moorings (not to scale).



Moored current meter (left) and density survey (right) arrays for MODE-1. The inner 100-kilometer circle represents an "accurate mapping" region, the outer circle a "pattern recognition" area.

transmitting from a shallower or deeper level. The ship would then go to another position, usually chosen to give a good "cut" between the two position circles. The ranges from the new position would be drawn and the intersection point would give the float position. The floats were each identified by a particular reply frequency.

The method proved to be extremely successful and particularly efficient in ship time. An indication of this is that during the 40 days spent tracking floats in MODE-1, 714 float-days of track were accumulated; this is to be compared with the total amount of float tracking since the first float was launched by NIO and including all the *Aries* measurements of 867 float-days.

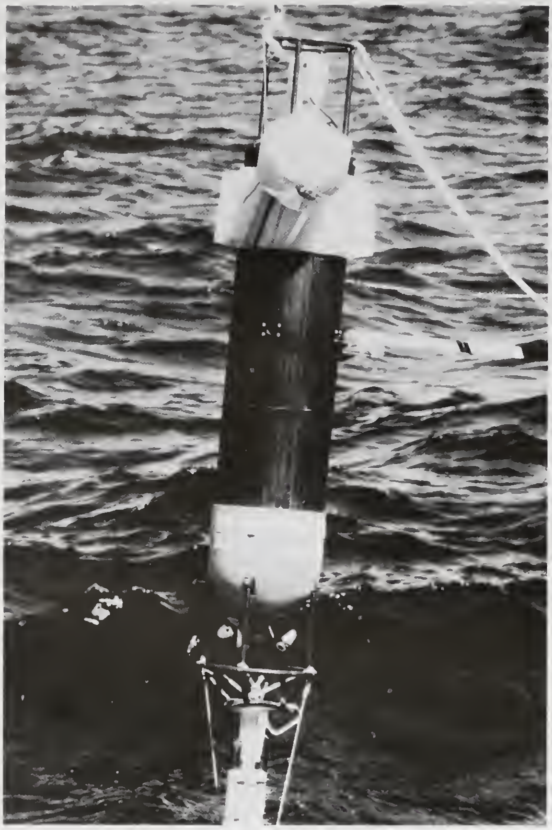
Some floats were lost (11 out of a total of 52 launches) due to faulty manufacture of release units; none was lost through inability to track the floats or to locate them once they had surfaced.

Vertical Profilers

All of the foregoing velocity measurements were restricted to discrete, predetermined depth levels. The more detailed vertical structure of horizontal velocities in the MODE-1 region was revealed by measurements from two types of profiling instruments. The first, T. Sanford's electromagnetic profiler, sensed the very weak electric currents induced in the seawater by its motion through the earth's magnetic field. It does not measure the absolute current velocity but rather the departure from some arbitrary offset that is dependent on both the true mean value of the current profile and a zero offset associated with the instrument. The profiler records the data internally as it free falls to the sea bed (the total time for a profile to 6000 meters is about 1½ hours), together with measurements of ambient pressure, seawater temperature, and electrical conductivity. The instrument resolution gives velocities to an accuracy of 1 centimeter per second at a vertical resolution of 10 meters.

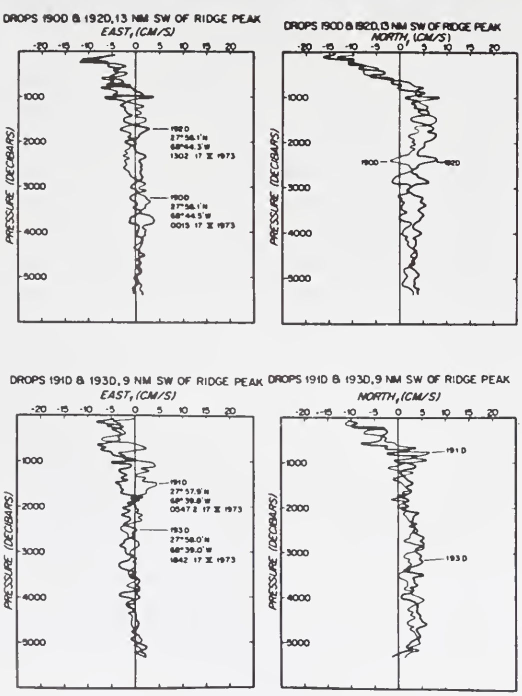
A somewhat simpler profiler that reveals absolute rather than relative profiles was used by T. Pochapsky. Here a slowly sinking float transmits to two transponders fixed on the sea floor. All the information from the floats is transmitted acoustically and received by an overside transducer on the attendant ship from which the float position may be fixed at regular intervals.

Both these techniques were expensive in terms of ship time required and thus were used for

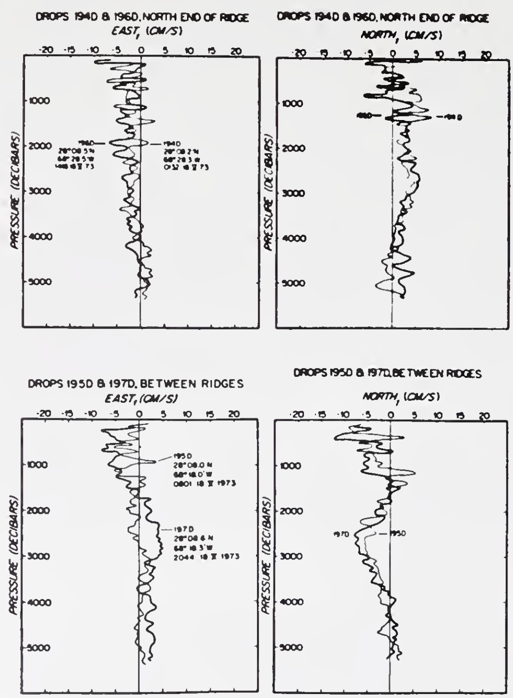


only limited periods and in a few selected positions in the MODE-1 region. An attempt to obtain vertical profiles over a wider region and throughout the period of the experiment was made using a rather simple air-dropped profiler. The system could be used to reveal the vertically averaged velocity from sea surface to the bottom or to any intermediate depth. A dropping aircraft ran along a predetermined line, launching the probes at intervals of about 4 kilometers. As the instrument reached the surface it produced a dye patch that drifted with the surface current. The profilers for intermediate and bottom depths were then released and sank at a known rate until a ballast was released by an internal clock. On return to the surface the profile probe released a second dye patch. A second aircraft then flew along the track photographing the dye patches. From the relative locations of the dye patches, one could determine the surface currents together with the averaged currents down to the depths of the profiles. About 1000 usable photographs were obtained from 1370 drops and gave a total of 960 measurements of either surface current or integrated flow over same depth range. Malfunctions of the timing clocks and the inability

(Top) Sanford's electromagnetic current profiler.
(Bottom) Some vertical profiles of horizontal currents as revealed by Sanford's electromagnetic profiler.



PROFILES OVER SMOOTH TOPOGRAPHY



PROFILES OVER ROUGH TOPOGRAPHY

of the photographing plane to find the dye patches proved to be the major sources of data loss.

STD and CTD Measurements

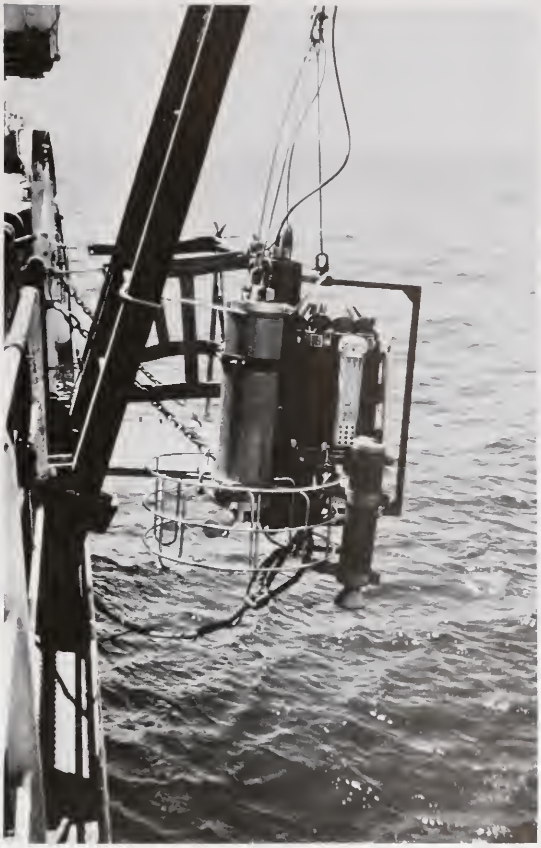
The study of the density field in MODE-1 was accomplished for the most part by the lowering of STD or CTD probes on conducting wires from the ships. These instruments provide continuous profiles as a function of pressure. Instruments such as these have been in general use since the late 1960s; in MODE-1 the major problem in using them was to ensure that even with different instruments on a variety of ships, each with slightly different operating procedures, a uniform data set could be achieved while still retaining a useful data accuracy.

The basic calibration technique is one not far removed from the classical water-bottle techniques. Samples of seawater were taken at a variety of points on each vertical CTD/STD profile, together with measurements of temperature and pressure determined by reversing thermometers. All the reversing thermometers had laboratory calibrations against some standard (typically quartz) thermometer. The conductivities of the water samples were measured on shipboard using laboratory salinometers.

Two samples were drawn from each sample bottle, and about 25 percent of these were then interchanged with other ships so that the laboratory salinometers could be intercompared. The coordination and intercomparison of the density data, since it involved so many people, proved to be a long process, but a final data set emerged that was sufficiently accurate to enable the density field to be mapped. The CTD/STD stations were worked on a fixed grid of 77 stations at a typical spacing of 33 or 50 kilometers.

The combined efforts of all the ships resulted in a complete survey of the density grid approximately once every 2 weeks, giving an adequate but not ideal amount of data from which to map the evolution of the density field. A large amount of ship time was required by this survey, each profile to 3000 meters and back to the surface taking between 2 and 3 hours. Some STD/CTD profiles were made to within a few meters of the sea bed; not all ships had long enough conducting cables to be able to do this, and on these vessels a separate water-bottle cast was worked to cover the lowest 2000 meters or so of the water column.

The data from the density grid survey were capable of later detailed analysis to reveal the dynamic implications of that field. The two-week interval between the surveys, together with the fact that each survey took two weeks, meant that the



A CTD (conductivity/temperature/depth) profiler. The sensors are within the protective cage around the lower circumference of the instrument. Above them is the pressure case containing associated electronics. Clustered sampling bottles with attached thermometer frames are for calibration purposes, while the cylinder with the downward-pointing mushroom-shaped transducer is an acoustic device to tell when the package is approaching the sea bed. (IOS)

details of sudden changes and small horizontal scales (smaller than the density grid spacing) could not be observed with these data. There were, however, other measurements that, although not directly of the density field, enabled these more detailed structures to be studied.

Temperature/Pressure Recorders

Most of the current meters, and certainly all of the VACMs, recorded water temperature every 15 minutes throughout the experiment. Each mooring had additional temperature and pressure recorders at a variety of depths throughout the water column. This resulted in a detailed series of temperature records with, in the case of the central mooring of the array, a total of 11 temperature time-series throughout the water column. The importance of the pressure record

is that it allows temperature recordings to be corrected for mooring motion. Even moorings with subsurface buoyancy are not entirely stable. As the strength of the current profile increases, so does the drag on the mooring; it leans over (just as a tree does in a wind) with the result that a point on the mooring line does not stay at a fixed level but moves up and down through the water column.

To a first approximation the density structure of the water column can be derived from temperature alone (since in any particular ocean area temperature and salinity have a quite well defined relationship to one another), and so these moored temperature records could be related to the CTD/STD measurements and could be used to supplement the density mapping.

XBTs

Although the moored T/P recorders could supplement the time evolution of the density field, the detailed horizontal structure on scales smaller than the density grid spacing had to be studied in other ways. Some ships were equipped with expendable bathythermograph (XBT) instruments that produce a profile of temperature as a function of depth in the uppermost 750 meters of the water column. The probes can be used from the ship as it steams at full speed, and although only temperature is measured—and not with the great accuracy of the CTD/STD systems—a detailed survey of a small area may be accomplished in a short space of time.

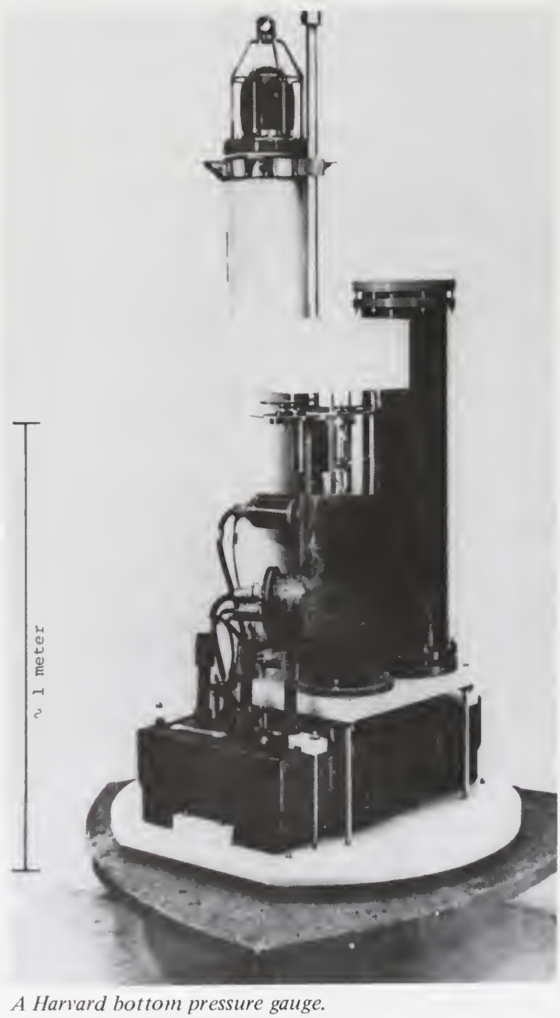
Towed STD

Just as the STD was used to make vertical profiles of the density structure, so it was also used on small horizontal scales to map the depth variations of a density surface. This was accomplished by towing a pair of underwater vehicles separated from one another by 10 or 20 meters, the upper one measuring pressure and temperature, the lower measuring pressure, temperature, and conductivity. By hauling in and paying out on the towing cable and by controlling the angle of a wing on the upper fish, the two towed sensors are controlled so that they straddle an isotherm. Four separate tows were made from the R/V *Chain* by E. Katz covering a total of 12 days. Each tow was worked on a regular closed pattern so that the depth of the density surface could be mapped over horizontal scales of up to 100 kilometers.

Indirect Measurements

In addition to the moored and shipboard instrumentation in MODE-1, there was a final category of measurements involving instrumentation that lay on the sea bed and recorded what might be regarded as "integrated" effects of mesoscale eddies. As the structure of the overlying water column changes, so does its mean density and hence the pressure at the sea bed. Because the variations are small and the total pressure signal large, the bottom-mounted pressure instrumentation had to be designed to detect and record variations in the pressure equivalent to 1 or 2 centimeters of water in the presence of an ambient pressure head of 5 kilometers (about 1 part in 10^5 or 10^6).

Three types of pressure recorders were used in MODE-1; the experiment was designed in part as an intercomparison with all three types near to one another at the central mooring and partly as a scientific study of abyssal pressure fluctuations. W. Munk of the Institute of Geophysics and Planetary Physics (IGPP) at the University of California, San Diego, used three quartz-crystal



A Harvard bottom pressure gauge.

pressure sensors; H. Mofjeld of the Atlantic Oceanographic and Meteorological Laboratory (AOML), three bourdon tube/optical lever sensors; and D. J. Baker, Jr., of Harvard University, five quartz bourdon tube/optical lever instruments.

Of the three, the IGPP capsule is the only absolute pressure gauge. The pressure sensor is a quartz crystal whose resonant frequency is a function of pressure. The aim with the IGPP instruments was to see if pressure signals (excepting those due to tides) could be detected above the noise level of the instruments and if the difference between two such measurements separated by 200 kilometers was resolvable. All the types of pressure sensors used in MODE-1 are affected by even the small temperature fluctuations found in the water of the abyssal ocean; therefore, each instrument measured temperature as well as pressure so that the pressure values could later be corrected. In the case of the IGPP instrument, the temperature sensor was also a quartz crystal, but it was cut in such a way as to respond to temperature changes and to be insensitive to pressure. In order to obtain the required redundancy, two of the three IGPP capsules were set close to the central mooring; the third, which was to detect horizontal pressure gradients, had dual sensors.

Both the AOML and Harvard recorders were similar in that each employed a mechanical pressure sensor that worked in a differential mode by measuring the departure from the pressure at the start of the record. Another similarity between the two types was that each used an optical lever arrangement to magnify the small pressure-generated mechanical distortions of the bourdon tube.

Both the AOML and IGPP instruments had been used extensively before MODE-1, and each gave a high return of data. The Harvard instruments were new, and although there had been previous test deployments from which good data had been retrieved, all the pressure-measuring systems in the MODE-1 field experiment failed due to a hitherto undetected fault in the servo mechanism used to track the movements of the optical lever.

The bottom-pressure experiment in MODE-1 did provide both useful insight into the performance of such instruments via the intercomparison at the central mooring and a new view of the long-term fluctuations of sea-bed pressure and their variability over distances of a few hundred kilometers.

Inverted Echo-Sounders

A novel new instrument, the inverted echo-sounder (IES), was used for the first time in MODE-1 in an attempt to study the temperature structure of the water column from an instrument on the sea bed. The principle on which this device works is as follows. The time for a pulse of sound to travel from the sea bed to the surface and back again is dependent on the total distance traveled (basically a constant apart from fluctuations in sea level due to the tides) and also on the mean value of the sound velocity in the water column. Thus a time series of the travel times may be corrected to represent the variations in the mean sound velocity. By regarding the water column, for the sake of simplicity, to be made up of an upper warm layer and a deep cold layer separated by a region of high temperature gradient, the thermocline, it can be seen that if the thermocline is displaced upwards, the relative amount of cold water in the column increases and the acoustic travel time increases.

Nine inverted echo-sounders were set in MODE-1, which, in spite of their newness, produced over 50 percent usable data. Variations in travel time were measured with an accuracy equivalent to a displacement of the 10°C isotherm of ± 4 meters, and comparisons with the data both from the moored temperature/pressure recorders and from CTD/STD stations later showed that an inverted echo-sounder was indeed capable of producing records that gave a good representation of the long period displacements of the main thermocline. The uncertainties in the IES data are of the same magnitude as the errors inherent in the CTD/STD data; for the study of integrated quantities over the entire water column the IES therefore represents a significant advance in being able to provide at least part of the data that would be collected from a CTD/STD survey but without the prolonged use of ships.

Shipboard Computers

In recent years shipboard computers have helped the oceanographer considerably in the collection, reduction, and analysis of his data while still at sea. Naturally, in MODE-1 computers played an important role. In all cases ships with CTD instruments recorded their data via a computer interface, and through this several derived quantities were available to the scientists while they were still at sea. Some of the ships employed computers in the routine navigation.

Summary

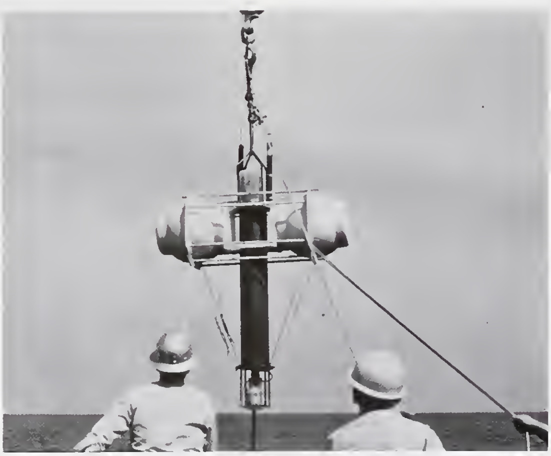
If we look beyond MODE-1 to future mid-ocean dynamics experiments, we shall perhaps see a change of emphasis. MODE-1 and POLYGON each studied one mesoscale feature for sufficient time to be able

to observe its propagation through a fixed moored array. We might expect future ocean dynamics experiments to involve the study of several features and over much longer time scales. It is not possible to contemplate such experiments relying on the continual availability of research ships. The demand for such ships for all kinds of research is so great, and the requirements for large numbers of scientists to remain at sea for long periods is unattractive. It is inevitable therefore that progress will be made towards the greater, and perhaps almost exclusive, use of remote recording techniques coupled with measurements that can be made from nonspecialized "ships of opportunity."

It has already been demonstrated that the horizontal velocity field can be mapped well over a large horizontal area by the SOFAR floats. The development of moored tracking stations would mean that such a system could be used anywhere in the ocean. Recent studies have shown that the restriction of placing the floats in the sound axis can be relaxed to allow floats to run at depths between 700 and 2000 meters. The inverted echo-sounders give the prospect of being able to map the gross features of the density field from an extensive array of instruments that, being on the sea bed, are free from disturbance by bad weather. Moorings will continue to play their part by carrying temperature and velocity recorders, but we shall perhaps see the introduction of current meters without the rotors and vanes that are vulnerable to damage and that have a threshold velocity often as great as the currents that the scientist is interested in observing.

Perhaps in MODE-1 we had not only an experiment that used the most advanced equipment available but also one in which the forerunners of a new generation of oceanographic instrumentation proved their worth.

W. John Gould is a principal scientific officer at the U.K. Institute of Oceanographic Sciences.



Deployment of an inverted echo-sounder (IES). Buoyancy is provided by two glass spheres in "hard hats."

GULF STREAM RINGS

by Philip Richardson

The Gulf Stream is the swiftest and most energetic current in the North Atlantic. One of the most interesting features of the Gulf Stream is the horizontal wave motions, or meanders, of its path; frequently these become sufficiently large to pinch off from the main current and form large eddies. The formation process is analogous to the cut-off highs and lows formed by the atmospheric jet stream. Gulf Stream eddies–their formation, movement, and decay–are vital in redistributing water, biological life (see page 69), and momentum and energy in the Gulf Stream system and western North Atlantic.

F. C. Fuglister has suggested the name *Gulf Stream rings* for these eddies because, during their formation, segments of the Gulf Stream form closed rings. Those formed to the south of the Gulf Stream have cyclonic (counterclockwise) circulation and contain cold Slope Water in their centers. Rings formed to the north are anticyclonic and contain warm Sargasso Sea water.

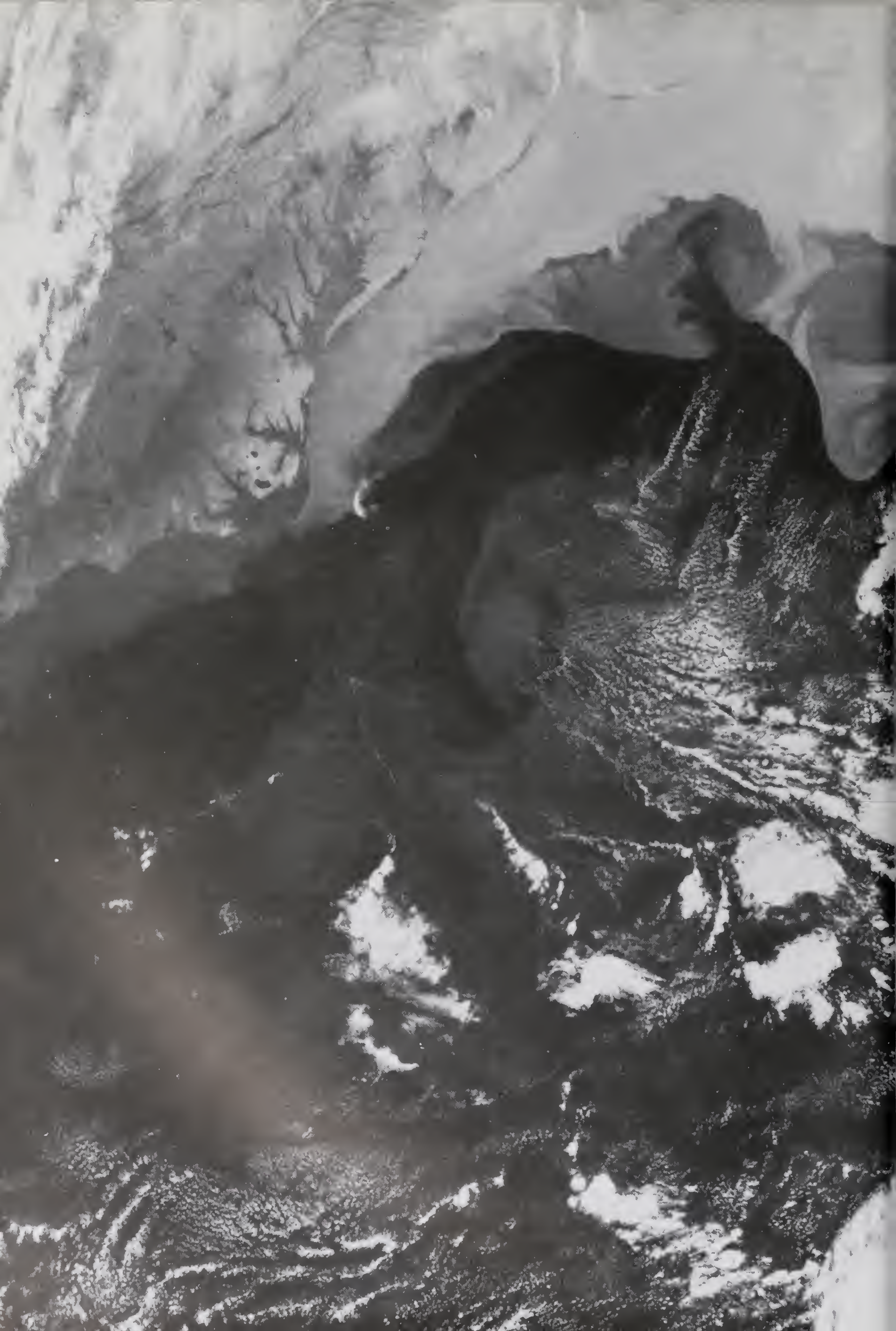
Although we have known about the existence of rings for almost 40 years, it is only during the last several years that we have learned about their distribution, long-term movement, and decay. Recent satellite infrared measurements, as well as ship and aircraft surveys, indicate that rings can be found in greater numbers in the western North Atlantic than we thought.

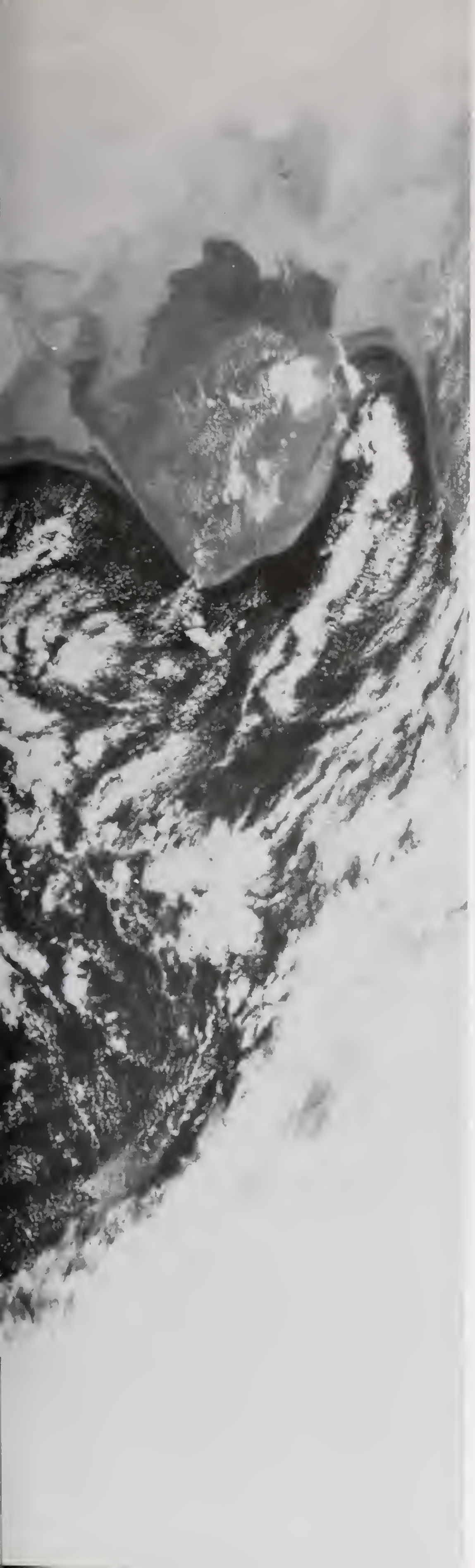
Advances in satellite measurement techniques have made it possible to view the Gulf Stream system from space over a wide region during a short period of time (less than a day). One of the best satellite infrared photographs is Figure 1, taken just off the U.S. East Coast, showing the Gulf Stream, two anticyclonic rings, and two cyclonic rings. The evidence suggests that the two anticyclonic rings that were first observed in January 1974 north of the Gulf Stream, moved west and south to coalesce with the Gulf Stream during the summer of 1974; the cyclonic rings south of the Gulf Stream both moved southwest, as other rings have been observed to do, and may have coalesced with the Gulf Stream off Florida during mid-1975; the Gulf Stream meander formed a cyclonic ring in June 1974, which was reabsorbed three months later near the place of its formation. Using successive satellite photographs and additional measurements, investigators at several oceanographic laboratories (including the National Oceanographic and Atmospheric Administration, the Naval Oceanographic Office, Research Triangle Institute, Texas A&M University, the University of Rhode Island, and the Woods Hole Oceanographic Institution) are trying to follow the evolution of these and other rings.

Distribution

Figure 2 is a synoptic representation of the Gulf Stream and rings at an instant in time. Since there has been no large-scale survey or good satellite coverage of the entire region, the figure is, for the most part, contrived, based on a wide assortment of data including recent satellite, aircraft, and ship surveys of portions of the area. North of the Gulf Stream we frequently see three rings at a time; south of the Gulf Stream and west of 50°W we can find approximately 8-14 rings. Some data suggest that rings can be found east of 50°W, but no thorough investigation has been made in this area. Only limited data exist for the region between 50°W and 60°W. Although rings have been observed to form only between 60°W and 70°W, their location east of 60°W and their westward movement indicate that they must also form east of 60°W.

The early stage of cyclonic ring formation is shown in Figure 2 near 38°N and 58°W where a large meander has trapped Slope Water in its "pocket"; the sides of the meander are closing, and the ring will separate from the Gulf Stream as shown





by the dotted lines. The southern boundary of the ring region is not well known. There is a lack of long-term ring tracking and detailed hydrographic surveys, and the decay of rings makes them more difficult to find when they are old. In any case, no rings have been documented south of about 30°N except for the extreme western region. Just north of the Bahamas several rings were seen very close to the Gulf Stream, apparently coalescing with it.

The initial sizes of rings differ; those north of the Gulf Stream are generally smaller than those to the south. The outer limits of rings are as difficult to determine as those of the Gulf Stream itself. In Figure 2 the Gulf Stream is shown as a band almost 100 kilometers wide, and the rings are from 150 to 300 kilometers in diameter. These limits represent, approximately, the locations where the main thermocline (the transition zone between warm surface water and cold, deep water) becomes horizontal and the current vanishes. The usual shape of rings is nearly circular, although significant variations are often found. There are limited but tempting data suggesting that rings may merge as well as break up into smaller pieces. Neither of these processes has been observed in detail, but they offer the simplest explanations of some observations.

Movement

Evidence for the movement of rings comes from the real-time tracking of a few rings by several techniques and from inferred trajectories based on an analysis of the National Oceanographic Data Center files of XBT (expendable bathythermographs) and hydrographic data. Rings north of the Gulf Stream move generally toward Cape Hatteras, with average speeds of 3-7 kilometers per day, where they have been observed to coalesce with the Gulf Stream. There is little variation from this mean movement because the rings are confined by the continental slope to the north and the Gulf Stream to the south. Cyclonic rings move south, away from the Gulf Stream, and then in a west and southwest direction. There appears to be a path offshore of the Gulf Stream between Florida and North Carolina along which rings typically travel. Approximately two rings per year follow this path

Figure 1. NOAA-3 infrared photograph of the Gulf Stream region off the U.S. East Coast from Florida to Massachusetts, April 28, 1974. Warm temperatures appear as dark shades, cold as light shades. The Gulf Stream is depicted as a dark band sweeping across the photograph. Two rings can be seen north of the Gulf Stream and two south of it. One ring to the south is outlined by warm Gulf Stream water that has been entrained by the ring's strong cyclonic flow. The second ring, farther south, is faint, but its existence was verified by ship measurement. Clouds appearing white can be seen in the southeast region. The dramatic effect of rings on at least the near-surface circulation of the ocean is clearly shown by the satellite data. (Courtesy of NOAA/NESS)

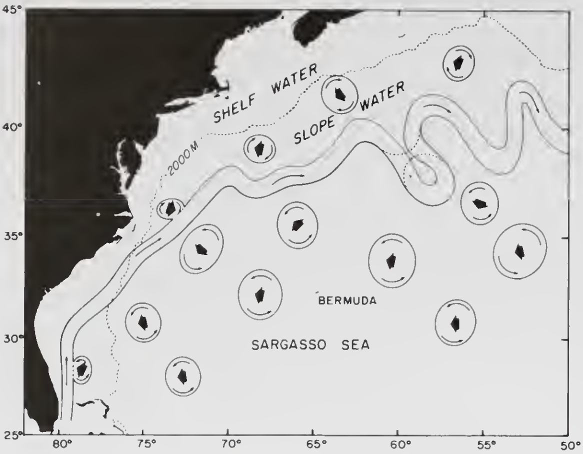


Figure 2. A schematic representation of the path of the Gulf Stream and the distribution and movement of rings. It is an attempt to summarize a number of studies that were made at different times and that usually focused on a smaller region.

at an average speed of 2 kilometers per day. The motion described here is long-term or mean motion; rings exhibit considerable variation from the mean over periods up to several months, and some coalesce with the Gulf Stream only a few months after formation. Rings sometimes move in complicated trajectories—for example, a looping clockwise motion with a speed of 10 kilometers per day, period of 60 days, and amplitude of 75 kilometers, as observed by Fuglister (personal communication).

The processes causing rings to move southwest have not been determined. Most mathematical models of rings predict a westward movement due to the Coriolis effect (see page 28). Rings may also be carried passively along with the mean ocean flow; their movement is consistent with what is known about the speed and direction of the return flow from the Gulf Stream. As the Gulf Stream flows north and then east, its volume transport increases dramatically, from about 30×10^6 cubic meters per second off Miami to approximately 150×10^6 cubic meters per second north of Bermuda. The Gulf Stream's transport then decreases as it flows toward the Grand Banks. Although there is at present a debate on just how the water is recirculated in order to account for the transport variation of the Gulf Stream, rings are clearly an integral part of this circulation. Each ring consists of a sizable portion of the Gulf Stream, approximately 500 kilometers in length and roughly 20 percent of the mean path from Cape Hatteras to the Grand Banks. Thus the formation, movement, and subsequent entrainment of rings by the Gulf Stream represents an important part of the return transport of Gulf Stream water, especially when one considers the large number of rings forming each year, estimated to be about 5-8 per year on each side of the Gulf Stream. For example, the volume transport associated with the formation and movement of 13 rings per year, each one consisting of a 500-by-100-by-2-kilometer section of the Gulf Stream is 41×10^6 cubic meters per second.

Decay

When rings were first seen, they were thought to have short lives of only a few months. Several recent time-series measurements continuing for more than a year indicate that some rings may last as long as 2 years. This long life is possible since most (95 percent) of the energy is in the form of potential energy; only a small portion is in the form of kinetic energy, which can be dissipated by friction. A young cyclonic ring has the main thermocline raised 500-600 meters in its cold core. This potential energy, on the order of 10^{24} ergs, is "available" to be released as the thermocline slowly subsides in the decay process to the mean Sargasso Sea background level. During decay, the peak tangential velocities in the high-velocity core remain strong, at approximately 100 centimeters per second, but move radially inward as the core subsides. The initial distinctive Slope Water characteristics of the core gradually disappear, indicating that the ring mixes with surrounding Sargasso Sea water.

Conclusions

Rings are interesting and worthy of study in their own right, but their important, though poorly understood, role in general ocean circulation makes it imperative that we learn more about them. A number of investigators are planning a large-scale study of rings, including surveys of distribution, tracking of trajectories, and detailed measurements of decay. We hope to combine theoretical modeling and field experimentation from a variety of disciplines into a unified study of rings.

Philip Richardson is an assistant scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution.

Suggested Readings

Barrett, J. R. 1971. Available potential energy of Gulf Stream rings. *Deep-Sea Res.* 18:1221-31.

Cheney, R. E., and P. L. Richardson. 1976. Observed decay of a cyclonic Gulf Stream ring. *Deep-Sea Res.* 23:143-55.

Fuglister, F. C. 1972. Cyclonic rings formed by the Gulf Stream 1965-66. In *Studies in physical oceanography,* ed. A. Gordon, pp. 137-68. New York: Gordon and Breach.

Parker, C. E. 1971. Gulf Stream rings in the Sargasso Sea. *Deep-Sea Res.* 18:981-93.

Stommel, H. 1965. *The Gulf Stream.* Berkeley and Los Angeles: University of California Press.

The Biology of Cold-Core Rings

by Peter Wiebe

The Sargasso Sea, until quite recently, was considered a fairly homogeneous body of water. Properties such as temperature and salinity were thought to be uniform over a vast area, with only minor seasonal changes, and these only within 100 to 200 meters of the surface. In addition, it has been said that "volume for volume the Sargasso Sea is the clearest, purest, and biologically poorest ocean water ever studied" (Ryther, 1956). This view of the uniformity in physical, chemical, and biological properties and the paucity of biological life is now changing rapidly, in part because of the discovery that Gulf Stream rings are a ubiquitous feature of the western North Atlantic, especially the northern Sargasso Sea (Parker, 1971).

For many years it was known that large cyclonic (counterclockwise) eddies frequently occur south of the Gulf Stream, but the formation of one such eddy was not observed until 1950, during "operation Cabot," the first multiship survey of the Gulf Stream. An eddy, or ring, is created when a large meander of the Gulf Stream breaks away forming a ring of swiftly moving Gulf Stream water (150-250 centimeters per second) around a core of seawater of different origin (see Figure 2, page 68). Rings forming to the south or east of the Gulf Stream entrap cold water from the continental slope and are known as cold-core rings. Those forming to the north or west of the Gulf Stream contain warm core water of Sargasso Sea origin. The cyclonic or cold-core rings are estimated to form 5 to 8 times a year (Fuglister, 1971). They are truly massive structures ranging horizontally from 150 to 300 kilometers and vertically from 2500 to 3500 meters when newly formed. Rings generally move south or southwest, gradually decaying as they travel. They have been known to persist as physically identifiable structures for two years or so. Recent unpublished data suggest that there may be as many as 15 cold-core rings wandering through the Sargasso Sea west of Bermuda at any given time.

Anticyclonic or warm-core rings are believed to form with equal frequency, but they are shallower structures (about 1000 meters deep) and they generally have a shorter existence (approximately 6 months) before coalescing with the Gulf Stream near Cape Hatteras (Saunders, 1971).

For the biologist, rings are of particular interest because during the process of ring formation, organisms originating in Slope Water or Subarctic Water are isolated within the cold-core structure. Since many of the Slope Water organisms are distinct from species living in the northern Sargasso Sea, the formation of a ring can be viewed as the beginning of a large-scale invasion of one oceanic community by another, with the concomitant intercommunity interaction. In fact, we now believe that the time-dependent events associated with the formation and decay of a cyclonic ring can be conceived of as a large-scale natural ecological experiment that offers the possibility of being able to separate the major effects of the physical-chemical environment on the structure and function of an oceanic community from the biological interactions among species. This is a problem of major importance today, stemming from the fact that in spite of our extensive knowledge about the large-scale dependence patterns of many oceanic organisms, we still cannot specify the factors that ultimately limit the distribution of any oceanic, planktonic organism.

Although both cold- and warm-core rings are of interest, we have concentrated on the cold-core structures because of their deeper vertical extent and longer duration.

Biological Effects of Changing Ring Structure

The first biological study of a cold-core ring was made in September 1972 on R/V *Atlantis II* cruise 71. During subsequent cruises, we surveyed five other rings and a large Gulf Stream meander (Figure 1), and measured the biomass (standing crop) of phytoplankton, zooplankton, and midwater fish,

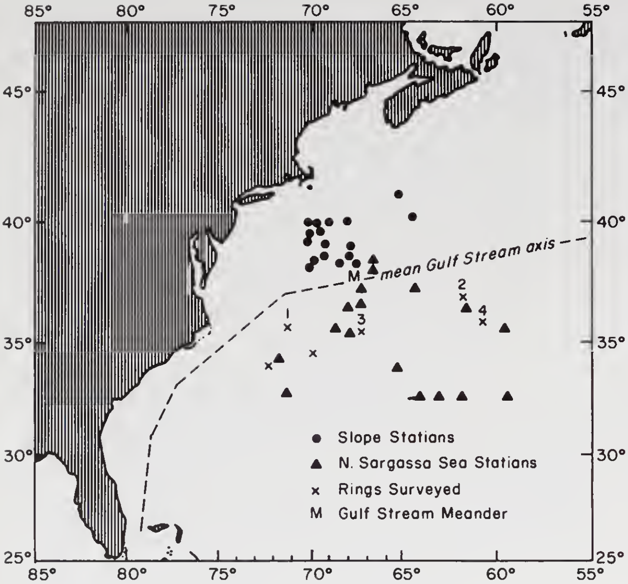


Figure 1. Distribution of cold-core rings surveyed and the location of Sargasso Sea and Slope Water stations used in comparisons. Numbered rings are those discussed in detail in the article. 1: Knorr *35, November 1973; 2:* Chain *111, February 1973; 3:* Atlantis II *71, September 1972; 4:* Knorr *38, March 1974. M represents the position of a Gulf Stream meander surveyed on* Atlantis II *85, October 1974. Some data from this meander are presented in Figure 7.*

and the primary productivity (turnover rate) of phytoplankton. At the same sampling locations, observations of temperature, salinity, and plant nutrients were made to define the rings and to assist in the interpretation of the biological data. In the discussion that follows, only data from the first four rings surveyed will be discussed in detail.

As rings age, they decay. The process of physical and chemical change can be seen in the warming and increasing salinity of the water, in the lessening nutrient content of the water column, and in the deepening of the oxygen minimum zone. (This zone occurs between 700 and 1000 meters in the northern Sargasso Sea but is much shallower, between 100 and 200 meters, in the Slope Water.) Similar changes are evident in the biota.

Although we have yet to sample a ring immediately after its formation, our work in a large meander and in two rings approximately 3 months old has suggested that the plant and animal biomass and species composition in newly found rings is nearly identical to the Slope Water that gave rise to the ring's core (Figure 2). Indeed, even after 3 months, the amount of chlorophyll *a*, a measure of phytoplankton biomass, can still exceed that found in the adjacent Sargasso Sea water by 50-60 percent. This was the case for a ring formed in late summer and sampled in mid-November of the same year. A number of factors, however, appear to influence the degree of contrast observed, and, as a result, rings of similar age differ substantially in standing crop of plant material. Thus, for example, on the February cruise, we found virtually no difference in plant biomass between a 3½-month-old ring and the surrounding area. This, we believe, was largely due to strong vertical mixing of the surface waters (upper 200 meters) caused by winter storm activity. Such disparate results are not as evident in the zooplankton. The biomass of zooplankton in the two young rings was higher than in the Sargasso Sea by 40-90 percent (Figure 1), but the difference between the two rings was less extreme.

The two older rings (8-12 months) sampled present a similar picture. Zooplankton biomass was generally lower than in the younger rings but higher than in the Sargasso Sea. In contrast, the distribution of plant chlorophyll was again one of extremes—essentially the same in the ring as in the surrounding waters on one cruise and approximately 65 percent higher on the other. The differences in plant biomass in these older rings also appeared to be a reflection of seasonally influenced processes. In this case the ring with the higher amount of chlorophyll was sampled in the spring, at a time when the "spring bloom" was underway; more nutrients were available within the ring, and primary productivity was higher. The other ring was sampled in late summer, when phytoplankton activity and standing crops generally reach a seasonal low in most temperate areas.

Fish biomass data from the various rings are more limited, but show a pattern similar to that of the zooplankton—one of decrease in biomass toward Sargasso Sea levels with increasing age of the rings.

Data on the effect of changing ring structure on species composition, while less extensive, exhibit a similar pattern of decrease in

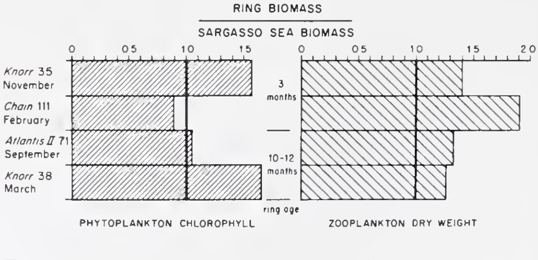


Figure 2. Ratios comparing cold-core ring and Sargasso Sea phytoplankton chlorophyll and zooplankton dry weight for rings of different age and time of year sampled.

the number of Slope Water forms with ring age. Phytoplankton species in samples from the 3-month-old November ring showed not only greater biomass, but also significant differences between the species composition in the ring and that in the Sargasso Sea. However, the phytoplankton species composition in the ring also differed significantly from that observed in the Slope Water. In fact, the ring species had a closer affinity with the Sargasso Sea species than with those in the Slope Water. Contrasting sharply was the 10-month-old September ring in which the phytoplankton biomass differed little from that of the Sargasso Sea. In this case there were no significant differences in the number of species or their abundance, or in the species composition.

For the zooplankton, analysis of species composition has focused on one particular group, the euphausiids, which are small shrimplike crustaceans (Figure 3). In sampling the slope, ring, and Sargasso Sea areas, we have encountered 32 species of euphausiids. Five species, *Euphausia krohnii, Meganyctiphanes norvegica, Nematoscelis megalops, Thysanoessa gregaria,* and *T. longicaudata,* are characteristic Slope Water forms and were numerically dominant in all Slope Water and in many ring samples thus far collected and counted (Figure 4). There were few of these species in the Sargasso Sea samples. Subtropical-tropical forms such as *E. brevis, N. microps, N. tenella, Stylocheiron affine,* and *S. suhmii* exhibit the opposite pattern, being most abundant in the Sargasso Sea and older rings, and much less evident in the Slope Water. In contrast, the more cosmopolitan species, *T. parva, S. carinatum, E. tenera,* and *E. hemigibba,* were found in considerable abundance in each type of water.

Individual patterns of abundance are reflected in the overall changes in species composition that seem to occur as a ring ages. In the younger rings the euphausiids show strong overall compositional similarity to those in the Slope Water, and generally weak similarity to those in the Sargasso Sea. The older rings, however, show a reverse pattern. Moreover, the younger rings with strong similarity to the Slope Water contain, on the average, twice as many individuals in the upper 800 meters of the water column as do the older rings with strong affinity to the Sargasso Sea species.

Sampling Instrumentation

Although it is almost certain that the changes in species composition and abundance are linked to the gradual change in the environmental conditions in the ring, we still do not know specifically what the causal factors are. This stems in part from the fact that our descriptions of the changes are very gross and lack the detail required to determine cause and effect. While rings appear to be very large hydrographic features, we, for example, have reached the point where simple towed nets and trawls can no longer provide sufficient resolution to enable us to elucidate the spatial relationships of the organisms. Furthermore, these instruments do not permit simultaneous collection of environmental information such as pressure, temperature, salinity, light, and oxygen, the small-scale fluctuations of which are considered to be important elements in shaping the distributional patterns of the organisms. The need for more sophisticated sampling gear became especially acute as we began to study changes with time in the vertical distribution of key Slope Water indicator species in the ring. (An indicator species is one that is generally restricted to a particular area or water mass and when found elsewhere indicates the water in which it typically lives is also present.) Substantial effort was therefore devoted to improving the zooplankton sampling instrumentation. This work resulted in the construction of a Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS), which has significantly enhanced our sampling capability (Figure 5).

The system carries nine nets that can be opened and closed sequentially on command through conducting cable from the surface. Environmental sensors to measure conductivity ($\pm$.001 percent), temperature ($\pm$.0005°C), and depth ($\pm$.01 meter) are attached to the net support frame. In addition, there are sensors to monitor flow past the net and the angle of the net assembly from the vertical, as well as indicators to record the electrical and mechanical function of the opening/closing mechanism. All data are transmitted up the cable to the shipboard computer for real-time processing.

Migration Patterns and Ring Decay

We have now successfully used this system (Figure 6) on three cruises—one to a Gulf Stream meander in October 1974 and two (August 1975, November 1975) to the same ring—to examine the diel (24-hour) vertical migration patterns of zooplankton in the rings, Sargasso Sea, and Slope Water (Figure 7). The euphausiids in the Gulf Stream meander cruise samples clearly show migration patterns for various species of the genus *Euphausia.* These species migrate downward at sunrise to depths of 350 to 700 meters, and upward at sunset to within 100 meters of the surface, with many appearing at

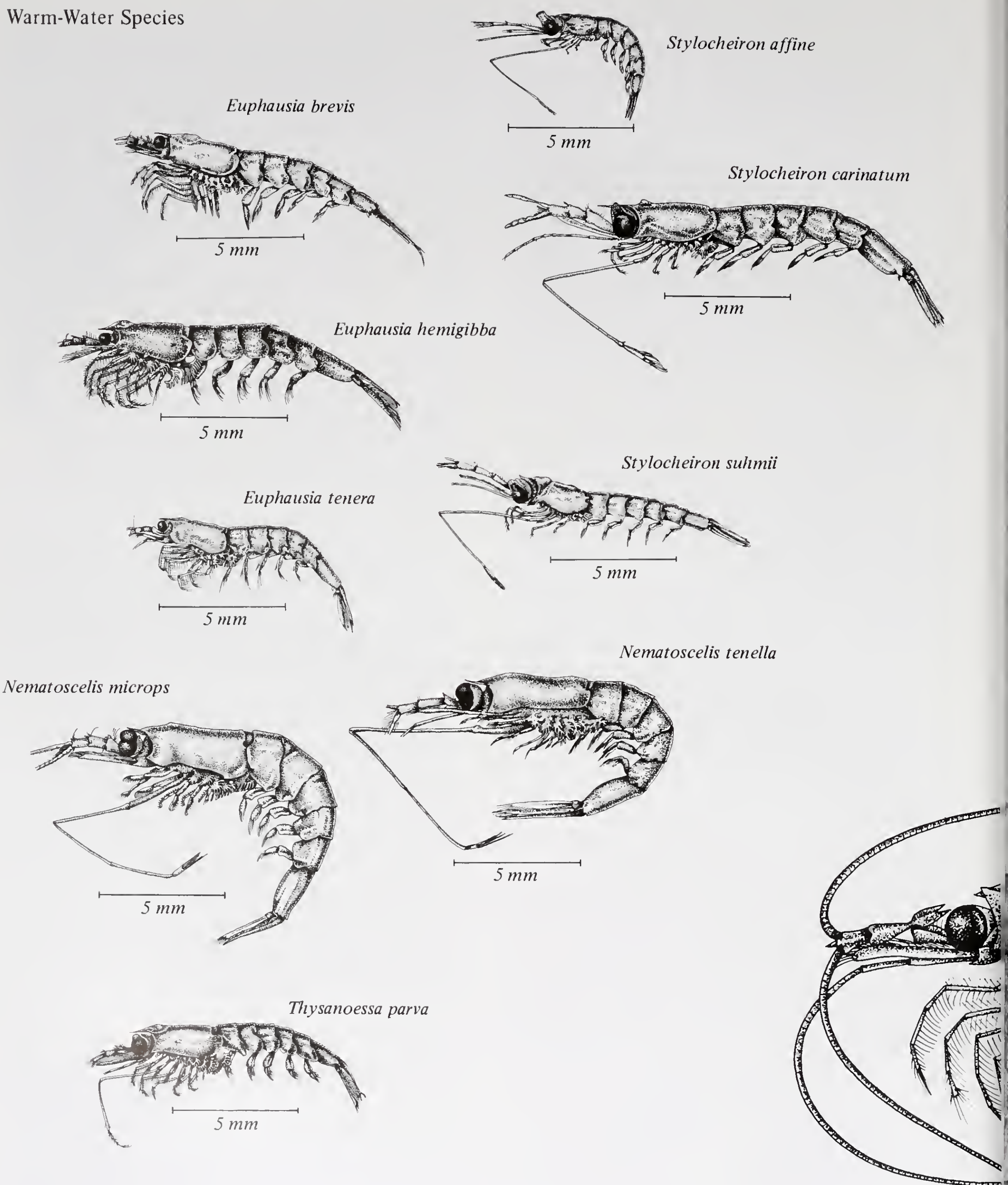
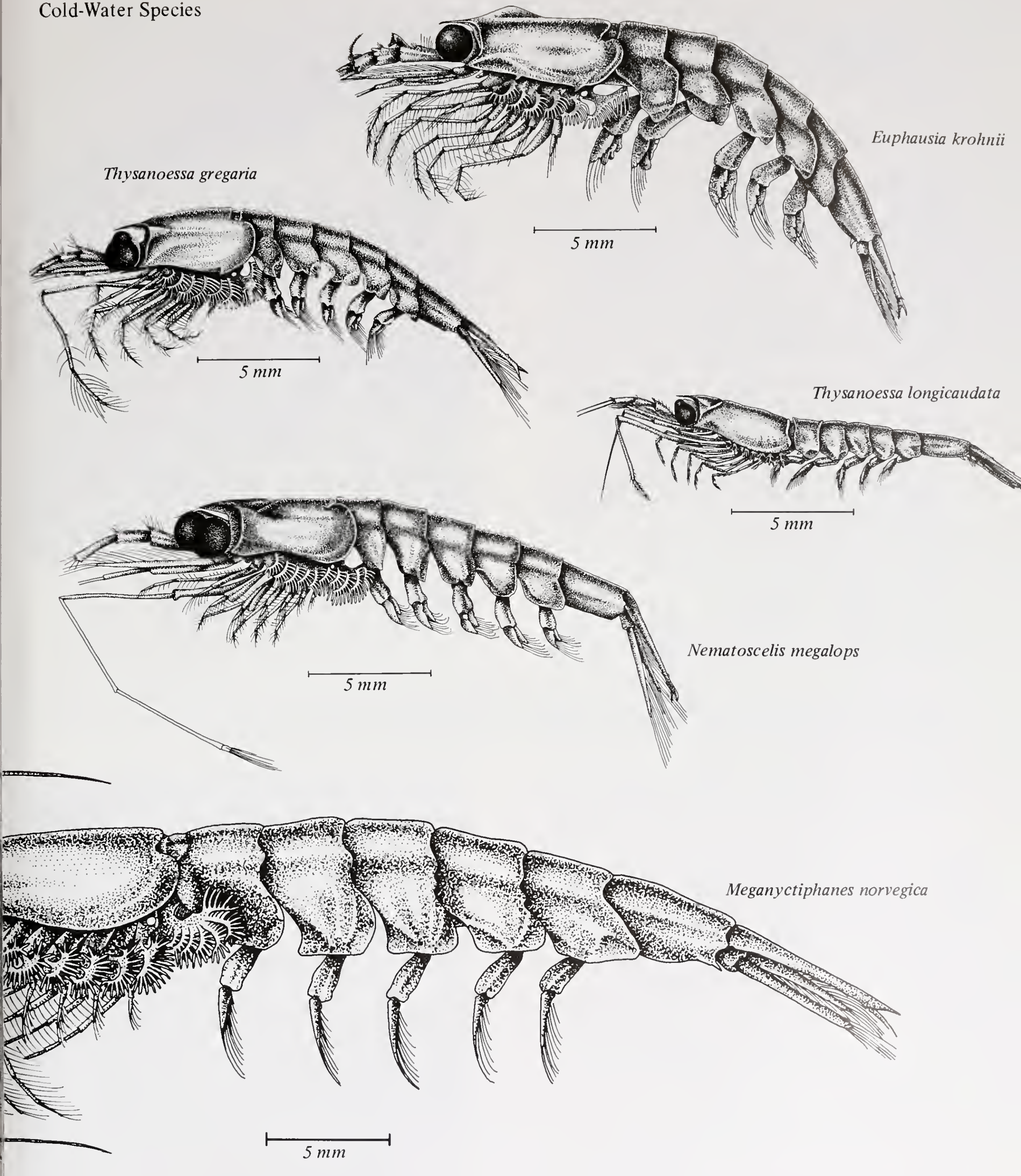


Figure 3. Euphausiid species more frequently encountered in the western North Atlantic where cold-core rings occur.

Cold-Water Species



(Drawings by Nancy Barnes, after B. P. Boden, M. W. Johnson, and E. Brinton, 1955, The Euphausiacea (Crustacea) of the North Pacific, *Berkeley and Los Angeles: University of California Press; E. Brinton, 1975,* Euphausiids of Southeast Asian Waters, *NAGA Rept., vol. 4, pt. 5, University of California, Scripps Institution of Oceanography; and H. Einarsson, 1945,* Euphausiacea 1. Northern Atlantic Species, *Dana Rept. No. 27.)*

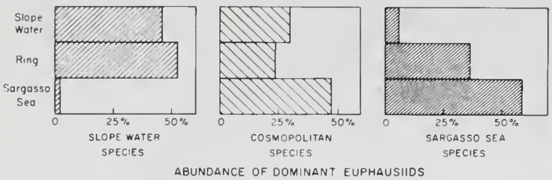


Figure 4. Relative abundance (%) of the dominant cold-water (Slope Water species) and warm-water (cosmopolitan and Sargasso Sea species) euphausiids in the Slope Water, ring, and Sargasso Sea.

the surface. In contrast, members of the genus *Stylocheiron* do not exhibit migratory behavior. These species, as shown in Figure 7, live in separate parts of the water column and overlap very little vertically. The data on presence and abundance of species in the Sargasso Sea, in combination with similar data from the meander and slope stations on this cruise, show the very strong contrast that exists across the faunal boundary marked by the Gulf Stream. There is a decrease in the abundance of warm-water species and an increase in the number of cold-water species, which coincides with the abrupt change in water properties. The daytime depth distribution for several typically warm-water species that were found at the slope and meander stations tended to be shallower in the colder, less saline water.

This kind of data forms a baseline, or background, and is necessary if we are to understand the changes in vertical distribution with ring decay that are distinct from basic patterns evident in home-range populations. It is the documentation

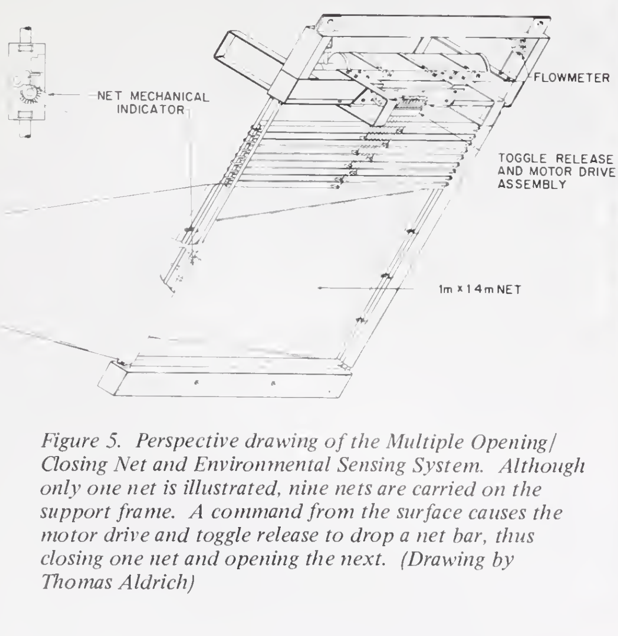


Figure 5. Perspective drawing of the Multiple Opening/Closing Net and Environmental Sensing System. Although only one net is illustrated, nine nets are carried on the support frame. A command from the surface causes the motor drive and toggle release to drop a net bar, thus closing one net and opening the next. (Drawing by Thomas Aldrich)

Figure 6. (Top) MOCNESS ready for launch over the stern of R/V Chain *(August 1975). Information from the net system sensors is transmitted through the cable on the winch in the foreground to the shipboard computer for processing. (Bottom) After a MOCNESS haul, each of the nine nets is washed to assure that no organisms are left on the meshes. After wash down, the animals in the cod-end buckets are transferred to glass jars, preserved, and taken back to the laboratory for measurement of biomass and enumeration of species.*

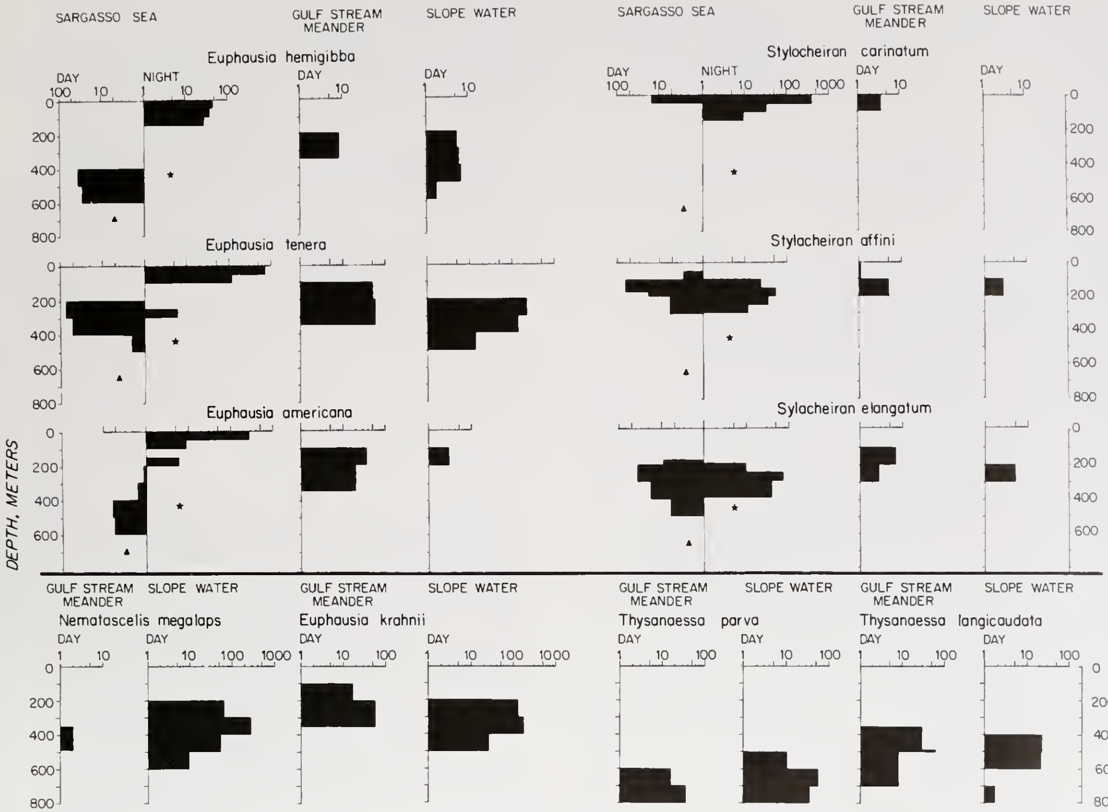


Figure 7. Vertical distribution of the more abundant euphausiids caught in four MOCNESS hauls (Sargasso Sea, day, night; Gulf Stream meander, day; Slope Water, day) taken on R/V Atlantis II *cruise 85. Warm-water species above; cold-water species below. Triangles and stars indicate maximum depths sampled.*

of changes in basic behavioral patterns, together with information about changes in the environmental setting, that should provide clues about the reasons for the change. For example, although our field and laboratory sampling have not progressed to the point where we can say definitively that migration patterns change with ring decay, there are suggestions in our data that this is the case. In particular, it appears that as a ring ages, the Slope Water forms live deeper in the water column and that their migrations to the surface are inhibited. Such changes could have a pronounced effect on the survival of the species. It is widely believed that one manifestation of the migration behavior is that migrators feed in the relatively food-rich surface waters at night and that little or no feeding takes place where they reside during the day (several hundred meters below the surface). If this is the case, and if the ring surface-water properties become unsuitable and the migrators no longer swim to the surface at night, then the individuals could be effectively excluding themselves from sufficient food. Their ultimate fate may be starvation. Thus, in addition to examining the migrations for changes in pattern, we are currently measuring the total lipid content of individual euphausiids caught in the MOCNESS tows in an effort to assess changes in the nutritional status of the expatriated ring populations. Here our preliminary results tend to support the contention discussed above. Lipid levels in ring-expatriated euphausiids in older rings are indeed much lower than those in individuals of the same species in the Slope Water.

Adding to the difficulty of interpreting the changes we have observed in species composition and abundance of the ring populations are the very large, natural variations in all oceanic populations. For example, a Slope Water indicator species has always been found to be the most abundant at some point in a ring, but no one species appears consistently as the numerical dominant. The species in the Sargasso Sea and in the Slope Water exhibit a similar pattern of shifting dominance. The statuses of the Sargasso Sea and Slope Water populations thus appear as critical determinants of

the initial biological structure of rings and their subsequent evolution. An obvious means to reduce the effect that the great variability in time and space has on our data is to obtain time-series measurements from a single ring starting from the time of formation. This we plan to do. Until recently our measurements have been obtained from different rings of different ages.

Of potential evolutionary significance is the fact that some cold-core rings coalesce with the Gulf Stream after a period of weeks to months. This may be a mechanism by which expatriated individuals are reunited with similar forms in their home range. If, as appears to be the case, populations of Slope Water species living in the rings are under increasing environmental stress, this stress may provide a progressive selection mechanism. Cold-core rings may therefore be a means by which genetically altered populations are introduced into the parent population. Since paleocirculation studies (Luyendyk, Forsyth, and Phillips, 1972; Berggren and Hollister, 1974) suggest that the Gulf Stream has been in its present position for millions of years, the process of ring formation and decay has probably been of importance for about the same length of time. Thus we may be observing a phenomenon that helped determine the limits of present-day biogeographic distributions of oceanic populations.

Conclusion

The discovery of rings and the evidence for their widespread occurrence in the western North Atlantic have provided oceanographers with a new and exciting area for research. Rings clearly offer a unique opportunity to study processes that are important to a determination of distribution and abundance of oceanic plants and animals. Although rings are best known in the western North Atlantic, similar hydrographic features are likely to be found in other western boundary current areas. Their importance to the physics, chemistry, and biology of the oceans is only beginning to be understood.

Peter Wiebe is an associate scientist in the Department of Biology, Woods Hole Oceanographic Institution.

References

Berggren, W. A., and C. D. Hollister. 1974. Paleogeography, paleobiogeography and the history of circulation in the Atlantic Ocean. In *Studies in paleo-oceanography,* ed. W. W. Hay, pp. 126-86. Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. No. 20.

Fuglister, F. C. 1971. Studies in physical oceanography. In *A tribute to George Wust on his 80th birthday,* ed. A. Gordon, pp. 137-68. New York: Gordon and Breach.

Luyendyk, B. P., D. Forsyth, and J. D. Phillips. 1972. Experimental approach to the paleocirculation of the oceanic surface waters. *Geol. Soc. Amer. Bull.* 83:2649-64.

Parker, C. E. 1971. Gulf Stream rings in the Sargasso Sea. *Deep-Sea Res.* 18:981-93.

Ryther, J. H. 1956. The Sargasso Sea. *Sci. Am.* January, pp. 77-81.

Saunders, P. M. 1971. Anticyclonic eddies formed from the Gulf Stream. *Deep-Sea Res.* 18:1207-19.

Mapping the Weather in the Sea

by James C. McWilliams

We live under the daily influence of the weather. It dictates many of our activities and some, perhaps many, of our moods. At the most primitive level, we can anticipate its influence simply by looking towards the horizon to see what might be coming. An extension of this, based only on the technology of being able to communicate rapidly over large distances, is drawing a large-scale weather map from a set of observations taken at nearly the same time. Such maps have been possible for over a century, and since 1870 they have been routinely drawn by the Army Signal Corps of the U.S. Weather Bureau (now called the National Weather Service).

Meteorology has become quite a sophisticated science: the observational archives are, by oceanographic standards, enormous; theoretical arguments are abundant; and forecasting by computer integration of the equations of motion has been performed for over twenty years. High hopes have been held for automated forecasting, but its performance has thus far been somewhat disappointing. Even today, an experienced synoptician can forecast from a weather map almost as well as a computer can. In practice, of course, weathermen now make their guesses after examining both synoptic maps and computer weather forecasts.

There can be no doubt, though, about the utility of mapping atmospheric synoptic-scale motions (the familiar "lows" and "highs" in pressure, cyclones, and anticyclones). Recently we have begun transferring these techniques to the field of physical oceanography. From MODE-1 (Mid-Ocean Dynamics Experiment), discussed throughout this issue, synoptic maps have been drawn for mesoscale ocean eddies (eddies with diameters of a few hundred kilometers). Since the data required for this exercise were both expensive and exhausting to obtain, these maps will be rare for some time to come. Furthermore, even if they could be used for forecasting, no one at present would see much value in this: the eddies directly influence few, if any, commercial activities, and their role in the broader issue of the earth's climate is years away from being understood. New skills generate their own demand, however, and I for one would be reluctant to predict what future uses may be made of these kinds of maps.

I am purposefully making an analogy between atmospheric synoptic-scale winds (what flows around a pressure anomaly on a weather map) and oceanic mesoscale currents. Many similarities do occur between them. Both are essentially geostrophic (that is, the fluid motions are directed parallel to lines of constant pressure). Both have nearly the maximum vertical scale possible, with currents related to each other over the whole of either the tropospheric height or the ocean depth. Both are the most energetic currents of any that occur in their respective fluids (for example, mesoscale eddies are more energetic than the ocean tides). Finally, it is plausible that both may arise spontaneously by tapping the energy of the permanent currents that are present—such as the prevailing westerlies or the Gulf Stream.

Obvious differences exist as well. The ocean eddies are relatively much slower (changing in months rather than days) and smaller (extending over hundreds, not thousands, of kilometers). However, we may argue that this is mostly due to the difference between water and air, particularly the way they are stratified. A useful manner of expressing the character of a fluid, based on a variety of theoretical models, is in terms of a horizontal length scale R, called the internal deformation radius. We define it by the formula

$$R = \quad g \frac{\triangle\rho}{\rho} h \quad 2\Omega \ \sin\ \lambda \ ,$$

where g is the gravitational acceleration on the earth, Ω the angular frequency of the earth's rotation, λ the latitude, $\triangle\rho/\rho$ the relative vertical change in

density (that is, the stratification strength), and h the vertical distance over which it occurs. For the ocean R_O = 50 kilometers, whereas for the atmosphere R_A = 800 kilometers; these are also typical scales for oceanic mesoscale and atmospheric synoptic-scale eddies.

The fact that aerodynamicists reproduce the real behavior of large airplane shapes in small wind tunnels demonstrates the success of mimicking a process through dynamically correct rescaling. We shall do the same thing here for atmospheric and ocean maps, where the rescaling is based on the deformation radius: ocean lengths should be smaller by the ratio R_O/R_A, and ocean time intervals should be longer by its inverse, R_A/R_O. (The rescaling in time is also based on a theory; namely, we assume that the actual currents are related to a phenomenon called Rossby waves [for Carl Rossby, a pioneer in theoretical meteorology]. In such waves, frequency is proportional to length, and length we have assumed proportional to R.)

Parallel sequences of maps are shown in Figure 1 for both the atmospheric ground level pressure and the oceanic pressure at 150 meters depth (minus the mean hydrostatic pressure at 150 meters, which can drive no currents). Actual distances on the page are equivalent by the relation described above (100 kilometers in the ocean equals 1600 kilometers in the atmosphere). Similarly, the time intervals between maps are approximately comparable (30 days and 2 days, respectively). The geographical domains have also been chosen to be comparable in size. The atmospheric region is narrower in latitude than longitude to avoid the tropical and polar regions—the motions there are phenomenologically distinct from mid-latitude cyclones and anticyclones.

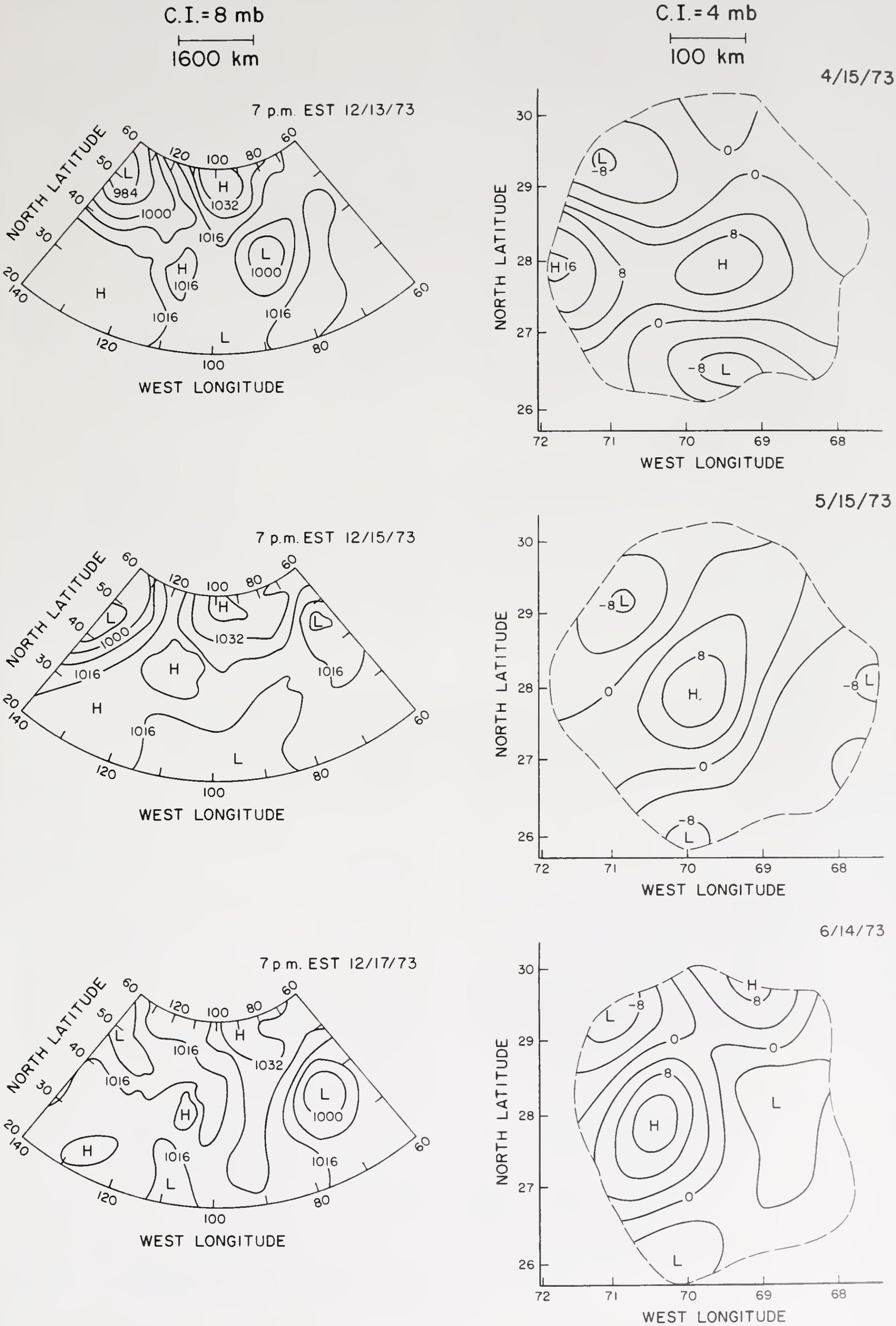
These maps allow us to better see how good the analogy between atmospheric and oceanic motions really is. They expose structural details and their time evolution, and thus contain a different kind of information than the summary characteristics mentioned above for oceanic and atmospheric eddies. Similar numbers of eddies appear in the two sets of maps; there also seems to be a comparable partitioning between high- and low-pressure centers. These centers retain their identities from one mapping period to the next. For some of the eddies, there seems to be a systematic motion towards the west (for example, the northwestern atmospheric low and the central oceanic high), but for others this is not true. Surely it would be foolish to try to generalize eddy behavior on the basis of the study of so few eddies for so brief an interval. The meteorologists have plenty of other maps; unfortunately, the maps of Figure 1 nearly span MODE-1, which is presently the only completed, four-dimensional mapping experiment for mesoscale eddies.

There are, of course, important structural differences between the two sets of maps (after all, it only rains in the atmosphere). Some are due to the different manners in which they were constructed—the number and distribution of observations as well as the techniques for drawing contour lines. (For example, the apparently greater amount of atmospheric small-scale structure, or contour wiggles, is strongly related to mapping technique.) Others may be related to the chance selection of which periods were mapped. No one eddy on the ocean maps can be expected to match identically any of the atmospheric eddies (disregarding the unlikely possibility that one set of eddies directly forces the other). In the face of these difficulties, I shall not attempt here to define the important inadequacies in the ocean/atmosphere analogy. For the remainder of this article, I shall neglect questions concerning techniques for drawing maps and the accuracy with which the end results are known—even though these are crucial issues for translating a pretty map into a scientific fact.

Many other maps can be drawn from MODE-1, for other depths and other times intermediate to the extremes shown in Figure 1. I would now like to illustrate from some of them various characteristics of mesoscale eddies.

Figure 2 is a schematic drawing of the vertical profiles of either the horizontal velocities or pressures (as mentioned above, these two quantities are proportional by the geostrophic relation) associated with ocean eddies. Two profiles have been drawn: we learned from MODE-1 that the vertical structure of currents was approximately a combination of these two simple structures. There are distinct patterns in time and horizontal position that are associated with each of these structures; during MODE-1 the patterns were reasonably, but not completely, independent of each other. The proportional magnitudes of the two profiles have been chosen in Figure 2 to represent the average conditions observed during MODE-1. We can see, therefore, that in and above the thermocline (above 750 meters), the observed currents were dominated by the structure that has vertical variation, while, at

Figure 1. A comparison of maps of atmospheric synoptic-scale eddies (left), as drawn by the National Weather Service, and oceanic mesoscale eddies. The maps are of surface pressure and of pressure at 150 meters depth, respectively. The atmospheric region spans the continental U.S.; the oceanic region is that of MODE-1. C. I. = contour interval on the maps.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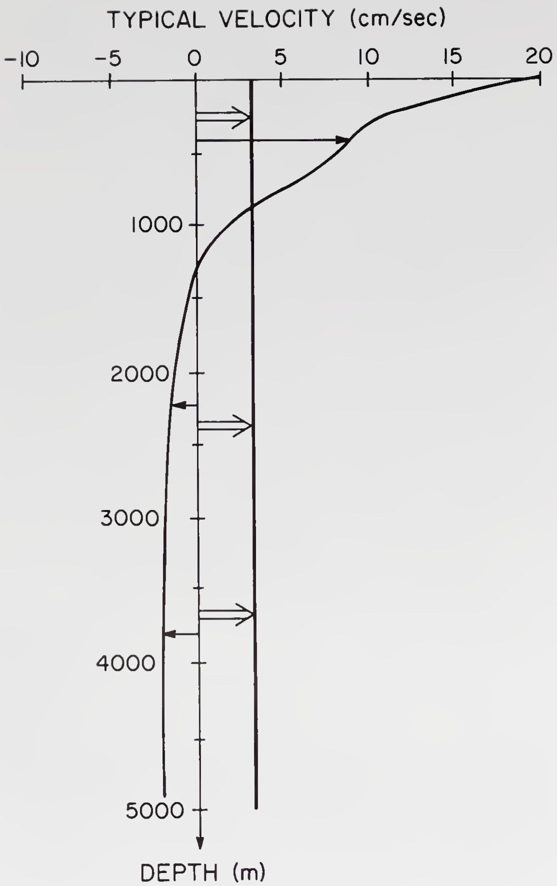

Figure 2. Schematic vertical profiles of horizontal velocity (or pressure) for the two predominant mesoscale eddy structures.

greater depths, the depth-independent structure dominated.

The patterns shown in the oceanic maps of Figure 1 illustrate the characteristics of the depth-variable structure. The type of observation that made the greatest contribution to exposing these patterns was measurements of water density (in a hydrostatic fluid, the pressure at a level is caused by the weight of fluid above it, and weight is volume times density). In contrast, the maps of Figure 3 are from 1500 meters depth, a region where the depth-variable contribution is virtually nil. These maps were constructed on the basis of trajectories of neutrally buoyant SOFAR (SOund Fixing And Ranging) floats (see page 57). The interval between the 1500-meter maps was chosen to be shorter (ten days), because the typical time required for a synoptic feature to change was less for the depth-independent structure. The time changes were perhaps less systematic at this level; however, the

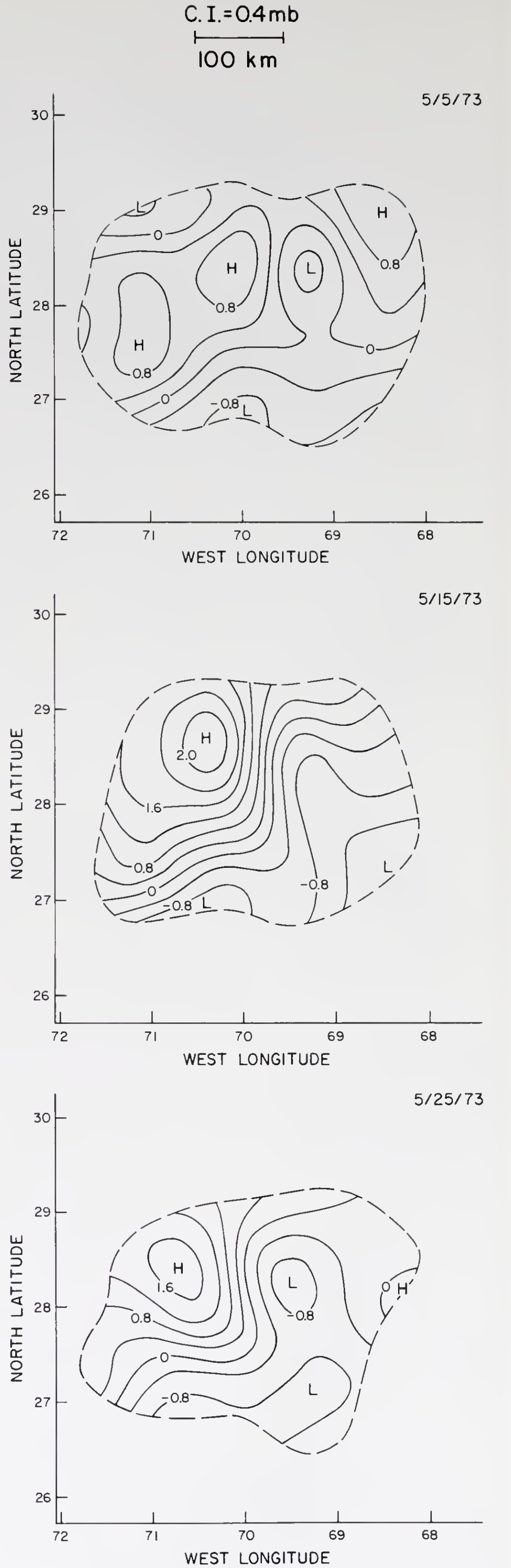

Figure 3. Maps of the ocean pressure at 1500 meters depth on three different days during MODE-1.

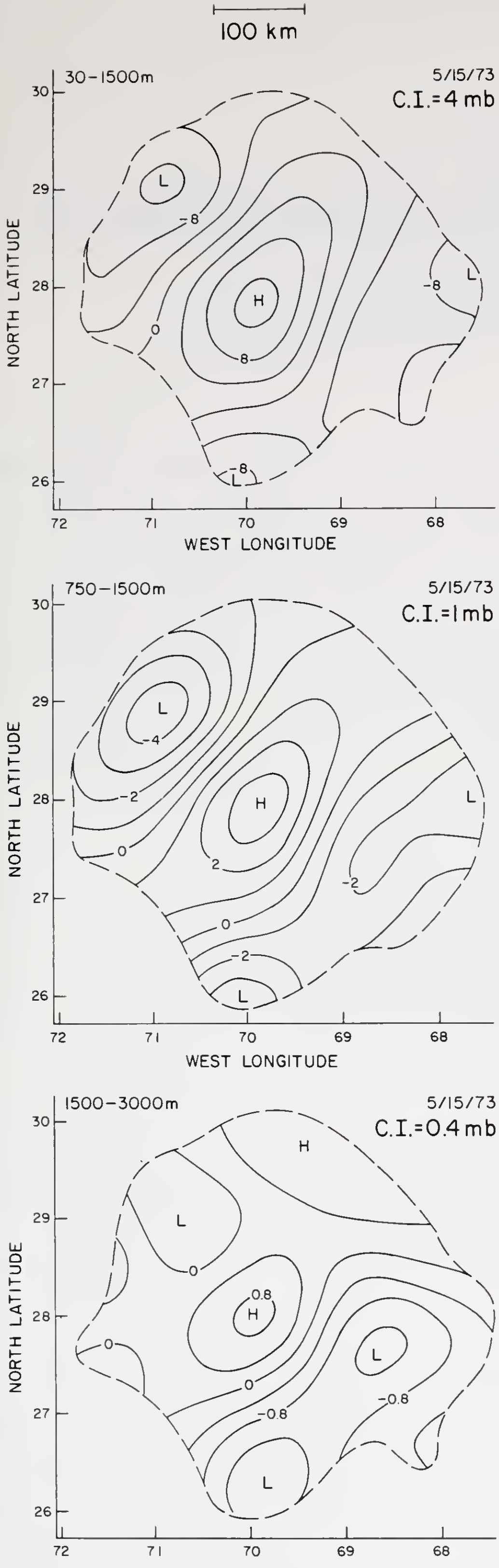

Figure 4. Maps of the vertical difference of pressure for three depth intervals on a particular day during MODE-1.

westward propagation of eddies seen in Figure 1 can also be detected here, though one gains confidence in this conclusion only after seeing a good many more maps than just those of Figure 3. The diameters of the 1500-meter eddies were relatively smaller as well, and the current speeds were much slower than at 150 meters.

The preceding claim about the ocean eddies involving only two vertical structures is, of course, an idealization, though it provides a useful summary of a number of complicated measurements. We can find some of the discrepancies from this claim in Figure 4, and at the same time see specific details of eddy patterns from top to (nearly) bottom. This figure presents patterns of the vertical differences in pressures between several depths on a particular day. If the ocean structure truly were as shown in Figure 2, then each of these patterns should be the same except for different overall magnitudes. This is because any vertical subtraction associated with the depth-independent structure would contribute nothing, leaving only the depth-variable profile. As one can see, the several maps in Figure 4 are similar, but not identical. They are, however, much more similar to each other than to the maps in Figure 3.

We obtained from MODE-1 the best set of mesoscale eddy maps yet available. They indicated eddy structures that were approximately a combination of the two profiles shown in Figure 2, with the corresponding horizontal patterns shown in Figures 1 and 3. What instruction can be taken from these maps, whether for the purpose of forecasting or allowing us to better understand the physical nature of the eddies, is yet unknown. There is certainly the atmospheric precedent, however, to encourage us that they may have great value.

James C. McWilliams currently works at the National Center for Atmospheric Research, Boulder, Colorado.

Suggested Readings

Gould, J., and H. Freeland. 1975. Objective analysis of mesoscale ocean currents. *Deep-Sea Res.* (submitted).

McWilliams, J. 1975. Maps from the MODE Experiment. I. Geostrophic streamfunction. *J. Phys. Ocean.* (submitted).

Sea Surface Temperature During MODE-1

by Arthur Voorhis and Elizabeth Schroeder

One of the most important oceanographic problems is the study of long-term variations in mean sea surface temperature. This temperature is an important factor in the energy exchange between ocean and atmosphere, and we must know more about it in order to assess past and future changes in world climate. Because surface temperature depends on many variable physical processes such as local solar and atmospheric heating and cooling, and turbulent heat exchange with underlying ocean layers, its measurement requires averaging a great many observations over a large area and over a long period of time. Major programs such as the North Pacific Experiment (NORPAX) in the United States and the Joint Air-Sea Interaction Experiment (JASIN) in the United Kingdom are active in this area.

The surface temperature at any fixed location is also affected by advection, that is, by surface currents that bring in warmer or cooler water from distant areas. This process can generate important changes in surface temperature, especially if large horizontal variations in temperature are present (for example, near the Gulf Stream) and if the currents are persistent and large-scale. Unfortunately, too little is known about such currents, particularly those on a scale of 100 to 500 kilometers. One of the few experiments designed to study currents in this range was MODE-1 (Mid-Ocean Dynamics Experiment), which was conducted in the area of the North Atlantic subtropical convergence during the spring of 1973 (see page 45). Recently we have correlated the currents with surface temperatures measured during MODE-1 and have concluded that the large-scale surface temperature pattern is largely the result of surface advection.

The subtropical convergence is one of the classical transition zones separating two meteorological wind regimes. In the western North Atlantic, it lies roughly between 22°N and 32°N latitude and separates the prevailing westerlies to the north from the easterly trades to the south. Maps of monthly mean sea surface temperature averaged over years of data present a relatively uncomplicated picture in the area eastward of the Gulf Stream's influence. This can be seen in the map for March in Figure 1. In general, the temperature decreases northward at all times of the year by an amount that varies seasonally. The maximum decrease occurs in late winter (approximately 0.5°C per degree of latitude, as shown in the figure) and the minimum in late summer (about 0.1°C per degree of latitude). The zonal (east-west) temperature variation is always very small. There are, however, major differences between this average picture and the synoptic temperature distribution (that is, the actual temperature distribution at any one time).

For over 10 years it has been known that the subtropical convergence is a region of pronounced surface frontogenesis. These fronts are often quite visible from shipboard or from the air (Figure 2). Observations show that these features separate adjacent surface water masses of differing temperatures (and densities). Although the distance across a front is usually quite short (less than 100 meters), with a horizontal temperature gradient two orders of magnitude greater than the mean meridional (north-south) gradient, they have been tracked as they meander along the sea surface for distances exceeding several hundred kilometers.

More recent and more dramatic evidence for large-scale variation in surface temperature comes from specially processed infrared satellite imagery of the sea surface, such as that in Figure 3, which clearly shows surface temperature dominated by meridional and zonal variations on a scale of several hundred kilometers. This is a marked contrast to the mean monthly picture (Figure 1).

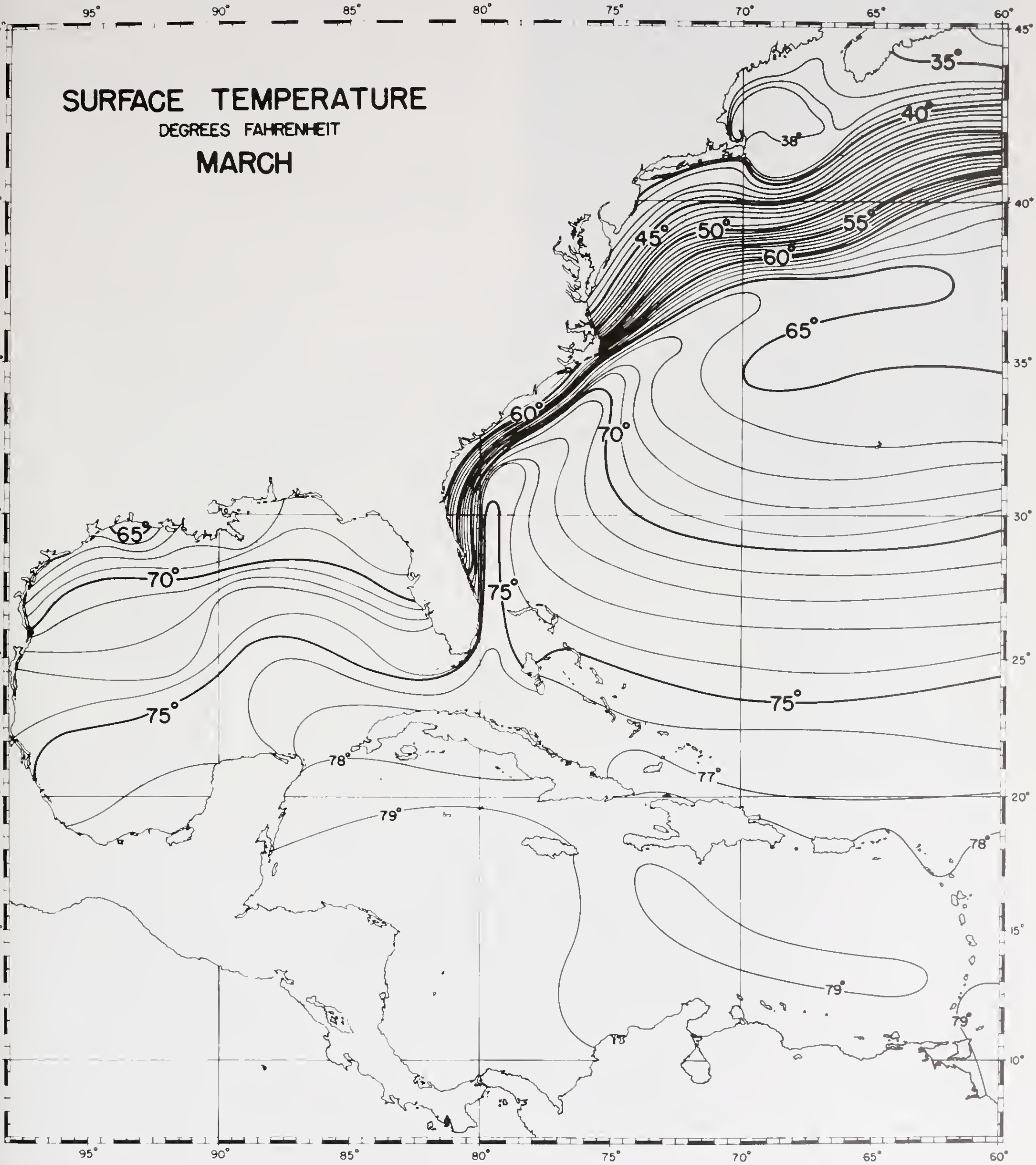

Figure 1. Mean March sea surface temperature in the western Atlantic and the Caribbean Sea. (After Fuglister, 1947)

Figure 2. Aerial photograph of surface debris collected along a surface front observed near 26°N 66°W in February 1965. (After Voorhis, 1969)

Eddy Surface Currents

Except for results of the *Aries* expedition in 1959-60 (see page 20), little was learned about the subsurface currents in this region until MODE-1. It is now known that these currents are dominated by large eddylike motions, which are for the most part confined to the upper 1500 meters of the water column. We asked ourselves whether these motions could be responsible for the large anomalies in the sea surface temperature field. Unfortunately, no usable satellite images of the sea surface during MODE-1 were available. However, continuous surface temperatures were recorded from three ships (R/V *Chain* and R/S *Researcher* from the U.S., and RRV *Discovery* from the U.K.) as they wandered about the area during the four months of the experiment. With these data plus results from more than 800 temperature and salinity soundings, we were able to construct temperature maps having reasonable spatial coverage for successive 15-day periods from the beginning to the end of MODE-1. These were then compared with maps that describe the eddy surface currents during the same time periods.

The sea surface temperature map for the period May 15-29 is shown in the top half of Figure 4, the corresponding (eddy) surface motion in the bottom half. The solid contours on the bottom map represent the surface dynamic topography relative to 1500 decibars that was computed from the temperature and salinity lowerings at the positions indicated by small dots. The eddy surface current direction is shown by the arrows, and its magnitude can be estimated from the speed scale in the lower right-hand corner of the figure. To facilitate the comparison between the two maps, we have shaded on the bottom drawing all those areas of the sea surface that are cooler than the mean temperature on the top illustration. The temperature map clearly shows a large-scale structure superimposed on a mean meridional trend of about 0.5°C per degree of latitude, with cooler water to the north. The resemblance, especially as to scale, between it and the satellite surface image in Figure 2 is striking.

The map of dynamic topography shows the famous MODE eddy that dominated the central region during most of the experiment. It appears on the figure as a hill on the surface having a height of about 10 centimeters and an average radius of about 150 kilometers. Around it flows an anticyclonic (clockwise) current with a speed of about 20 centimeters per second. It takes almost one month for surface water to make a circuit of the eddy. A visual comparison between the maps of temperature and dynamic topography strongly suggests that eddy surface currents are primarily responsible for the large-scale structure seen in the temperature map. Note the warm southern water advected northward along the western side of the eddy and the cooler northern water carried to the south along its eastern side.

All of the temperature maps of the MODE area (and those of dynamic height) show similar large-scale patterns, but they change with time. Temperature maps are usually dominated by the long (200 kilometers) alternate intrusions of warm and cool water seen in Figure 4. These intrusions seem to last 20 to 30 days, which is approximately the circuit time for an eddy but much less than the lifetime of the eddy itself (about 90 days). It is for this reason that temprature maps show very little spiral structure; that is, the long tongues of warm or cool water appear to be carried by surface currents only once around an eddy. The duration of an eddy is, of course, controlled by the internal dynamics of the ocean. On the other hand, we believe that the persistence time for the long advected features of the surface temperature field is controlled mainly by heat exchange with the atmosphere.

Surface fronts similar to those in Figure 2, were often seen from shipboard during MODE-1, and the continuous surface temperature records show numerous frontal crossings. Because the fronts were carried along rather rapidly by the eddy surface currents, it was simply not possible to map their position in any detail from the rather random ship crossings. In retrospect, it seems unfortunate that none was tracked by ship or from the air. Nevertheless, our data suggest that most of the fronts occurred in areas where there were substantial horizontal changes, or gradients, of surface temperature and where the eddy surface flow was such as to maintain these gradients. This situation usually occurred along the boundaries of the long lateral intrusions seen in the temperature maps. Such frontogenic areas in Figure 4 are in the vicinity of 27.5°N 71.0°W and 28.5°N 69.0°W. This rather vague observation is supported by the theoretical work of Hoskins and Bretherton (1972), who have worked with a density-stratified fluid to study surface frontogenesis by a large-scale current field. One finds, using the Hoskins-Bretherton analysis, that surface fronts can form in some areas in three to five days.

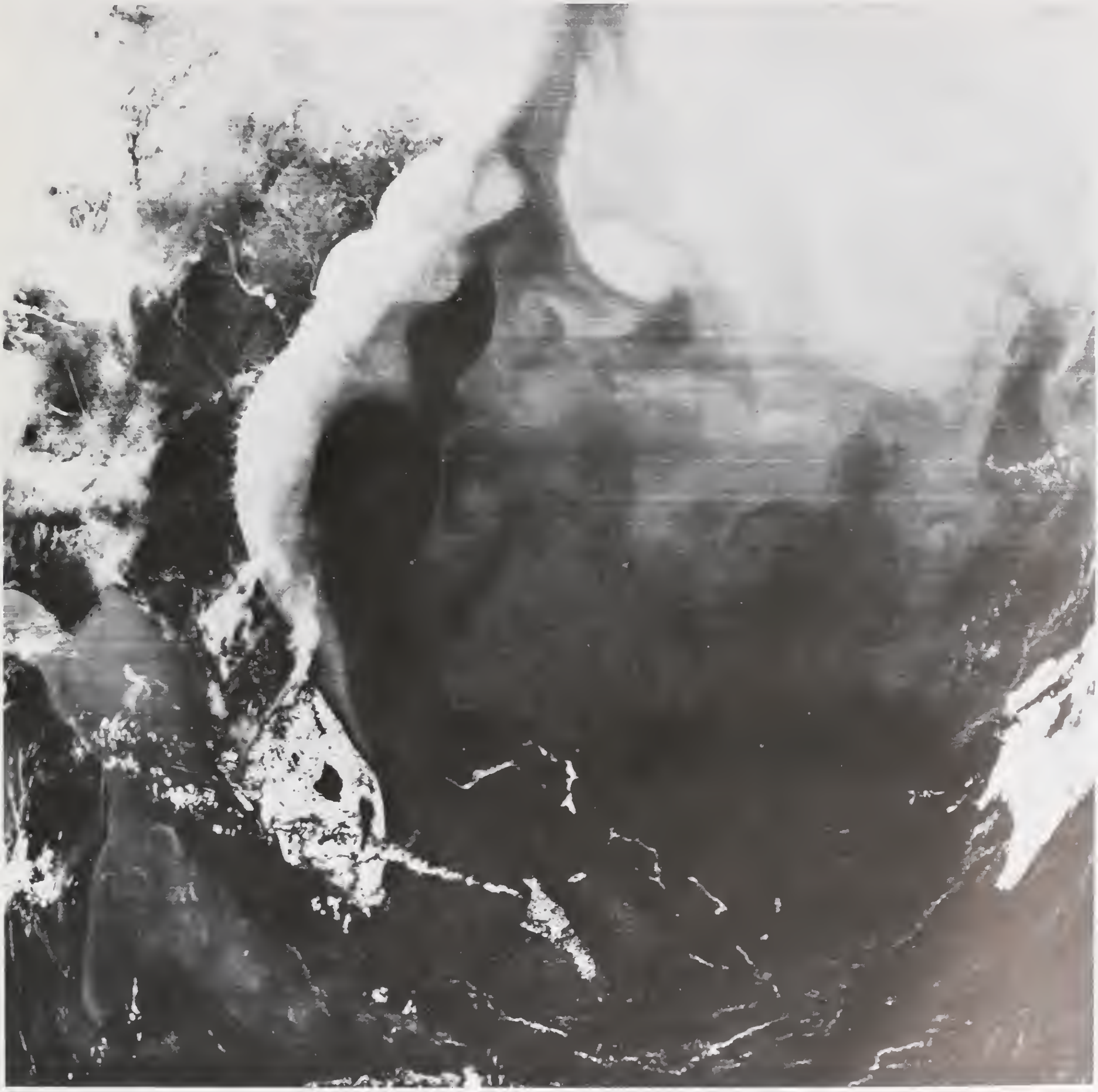

Figure 3. Enhanced infrared satellite image of the sea surface in the western North Atlantic showing large-scale advective patterns on April 1, 1974. Dark regions are warm water, grey are cool water; white areas are clouds and should be ignored. (Courtesy of R. Legechis, NOAA/NESS)

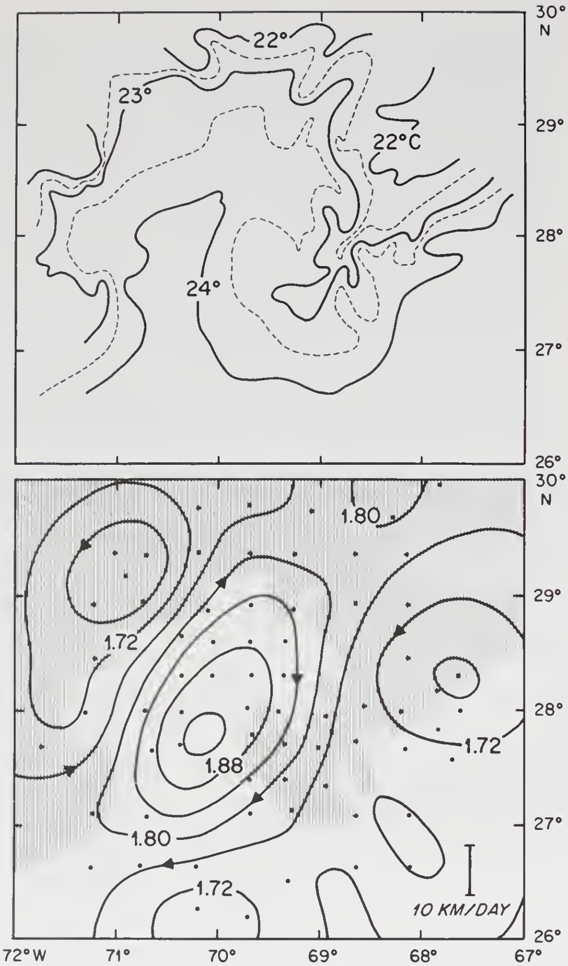

Figure 4. Sea surface temperature map (top) and dynamic topography (bottom), relative to 1500 decibars, of the MODE area for the period May 15-29, 1973. The shaded area on the bottom map shows surface water that is cooler than the mean temperature of the top map. The eddy surface current speed is inversely proportional to the spacing between the contours of dynamic height and is equal to 10 kilometers per day when the spacing is equal to the scale shown in the lower right-hand corner. (After Voorhis and Schroeder, 1976)

Conclusion

A question arises from the material presented here that has important implications for oceanographers who are interested not only in the large-scale eddy field covered by MODE-1 but also in other parts of the world ocean: Can the knowledge of the time-varying spatial structure of surface temperature (or other properties), measured from satellite or by rapid ship surveys, contribute significantly to the understanding of these motions? We believe the answer is yes, although a great deal more work must be done. For example, it is clear from our maps that surface isotherms do not coincide with contours of dynamic height. This is mainly due to the fact that the eddy currents are continually changing with time. Therefore, in order to infer something about the currents from temperature, we need a rather complete knowledge of all the relative time scales involved. This includes the variation of mean surface temperature gradients, of the eddy field, and of the temperature structure created by this field.

Summarizing our results, we conclude that surface currents from large-scale eddies are responsible for large-scale, slowly changing patterns in the sea surface temperature, both in the MODE area and, probably, in many other areas of the world ocean. For the oceanographer and meteorologist interested in annual or longer-term changes in the mean sea surface and their effect on climate, these varying temperature patterns are unwanted noise and introduce a further uncertainty into their measurements.

Arthur Voorhis is an associate scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution. Elizabeth Schroeder is a research associate in the same department.

References

Fuglister, F. C. 1947. Average monthly sea surface temperatures of the western north Atlantic Ocean. *Pap. Phys. Oc. and Meteor.* 10(2), 25 pp.

Hoskins, B. J., and F. P. Bretherton. 1972. Atmospheric frontogenesis models: mathematical formulation and solution. *J. Atmos. Sci.* 29:11-37.

Voorhis, A. D. 1969. The horizontal extent and persistence of thermal fronts in the Sargasso Sea. *Deep-Sea Res.* 16:331-37.

Voorhis, A. D., and E. H. Schroeder. 1976. The influence of the deep mesoscale eddies on sea surface temperature in the North Atlantic convergence. *J. Phys. Ocean.* (in press).

Oceanus welcomes Oceanus

Latest addition to the research vessels of Woods Hole Oceanographic Institution is R/V *Oceanus*. Designed to be economical as well as efficient, she is 177 feet in overall length. Range at maximum cruising speed of 14.5 knots is 8000 nautical miles. Complement is 13 officers and crew, and 13 members of the scientific party. She and we take our name from the Titan who fathered the gods of the rivers and the nymphs of the sea. *(Photo by Peterson Builders, Inc.)*

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SEA-FLOOR SPREADING, Winter 1974–Plate tectonics is turning out to be one of the most important theories in modern science, and nowhere is its testing and development more intensive than at sea. Eight articles by marine scientists explore continental drift and the energy that drives it, the changes it brings about in ocean basins and currents, and its role in the generation of earthquakes and of minerals useful to man.

AIR-SEA INTERACTION, Spring 1974–Air and sea work with and against each other, mixing the upper ocean, setting currents in motion, building the world's weather, influencing our lives in the surge of a storm or a sudden change in patterns of circulation. Seven authors explain research in wave generation, hurricanes, sea ice, mixing of surface waters, upwelling, long-range weather prediction, and the effect of wind on circulation.

ENERGY AND THE SEA, Summer 1974–One of our most popular issues. The energy crisis is merely a prelude to what will surely come in the absence of efforts to husband nonrenewable resources while developing new ones. The seas offer great promise in this context. There is extractable energy in their tides, currents, and temperature differences; in the winds that blow over them; in the very waters themselves. Eight articles explore these topics as well as the likelihood of finding oil under the deep ocean floor and of locating nuclear plants offshore.

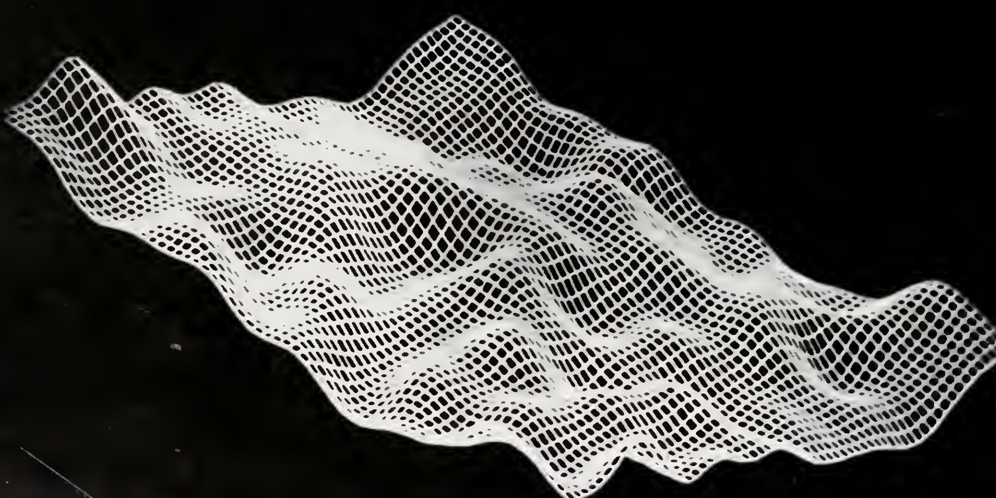
MARINE POLLUTION, Fall 1974–Popular controversies, such as the one over whether or not the seas are "dying," tend to obscure responsible scientific effort to determine what substances we flush into the ultimate sink, in what amounts, and with what effects. Some progress is being made in the investigation of radioactive wastes, DDT and PCB, heavy metals, plastics and petroleum. Eleven authors discuss this work as well as economic and regulatory aspects of marine pollution.

FOOD FROM THE SEA, Winter 1975–Fisheries biologists and managers are dealing with the hard realities of dwindling stocks and increasing international competition for what is left. Seven articles explore these problems and point to ways in which harvests can be increased through mariculture, utilization of unconventional species, and other approaches.

DEEP-SEA PHOTOGRAPHY, Spring 1975–A good deal has been written about the use of hand-held cameras along reefs and in shallow seas. Here eight professionals look at what the camera has done and can do in the abyssal depths. Topics include the early history of underwater photography, present equipment and techniques, biological applications, TV in deep-ocean surveys, the role of photography aboard the submersible *Alvin* along the Mid-Atlantic Ridge, and future developments in deep-sea imaging.

THE SOUTHERN OCEAN, Summer 1975–The first of a regional series (in planning are issues on the Mediterranean and Caribbean) examining important marine areas from the standpoint of oceanographic disciplines most interested in them. Physical, chemical, and biological oceanographers discuss research in antarctic waters, while a geologist looks at the ocean floor, meteorologists explain the effect of antarctic weather on global climate, and a policy expert sets forth the strengths and weaknesses of international scientific and political relations in the area.

SEAWARD EXPANSION, Fall 1975–We have become more sophisticated in our offshore activities than is generally realized. Eight articles examine trends in offshore oil production and its onshore impacts; floating oil ports; artificial islands; floating platforms; marine sand and gravel mining. National and local policy needs are examined in the light of the move seaward.



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